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International VLBI Service for Geodesy and Astrometry 2015+2016 Biennial Report

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December 2017

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Preface

This volume of reports is the 2015+2016 Biennial Report of the International VLBI Service for Geodesy and Astrometry (IVS). This volume documents the work of the IVS components for the calendar years 2015 and 2016, our seventeeth and eighteenth years of existence. This is the first in a series of biennial reports; the first sixteen years of the IVS were documented annually. It is the hope of the IVS Directing Board that beginning a biennial reporting period will reduce the cost of the report and most importantly the efforts invested by the IVS community in documenting our work.

The individual reports were contributed by VLBI groups in the international geodetic and astrometric community that constitute the permanent components of IVS. The reports describe changes, activities, and progress of the IVS. Many thanks to all IVS components who contributed to this Biennial Report.

The contents of this Biennial Report also appear on the IVS Web site at

`http://ivscc.gsfc.nasa.gov/publications/br2015+2016`

This book and the Web site are organized as follows:

- The first section contains general information about the IVS, a map showing the locations of the components, information about the Directing Board members, and the biennial report of the IVS Chair.
- The second section holds a special report. In May 2017, the Task Force on IVS Intensives produced a report that reviews recent IVS research into the Intensives and suggests future improvements for the Intensives. This report is included here, with a few updates, including the addition of recent information about VGOS Intensive research.
- The next seven sections hold the reports from the Coordinators and the reports from the IVS Permanent Components: Network Stations, Operation Centers, Correlators, Data Centers, Analysis Centers, and Technology Development Centers.
- The next section contains a compilation of publications in the field of geodetic and astrometric VLBI during 2015 and 2016.
- The final section provides reference information about IVS. Following the current (September 23, 2011) version of the IVS Terms of Reference, a reference table is provided with links to the IVS Member and Affiliated organizations, the IVS Associate Members, and the IVS permanent components.

Table of Contents

Preface iii

About IVS 1

IVS Organization 2
IVS Component Map 4
IVS Directing Board 6
IVS Chair's Report 8

Special Reports 11

Task Force on IVS Intensives: Updated Final Report 13

IVS Coordination 21

Coordinating Center Report 23
Analysis Coordinator Report 26
Network Coordinator Report 29
IVS Technology Coordinator Report 37

Network Stations 41

Moving from TIGO to AGGO: Argentinean-German Geodetic Observatory (AGGO) Report 43
Badary Radio Astronomical Observatory 2015–2016 Report 48
Effelsberg Radio Observatory 2015–2016 Biennial Report 51
Fortaleza Station Report for 2015 and 2016 54
Goddard Geophysical and Astronomical Observatory 57
Hartebeesthoek Radio Astronomy Observatory (HartRAO) 60
AuScope VLBI Array and Hobart 26-m Antenna 65
Kashima 34-m VLBI Network Station Report for 2015—2016 70
Kokee Park Geophysical Observatory 75
Kashima 11-m and Koganei 11-m VLBI Stations 79
Matera CGS VLBI Station 2015–2016 Biennial Report 83
Medicina Station Status Report 86
Metsähovi Radio Observatory Network Station 2015–2016 Biennial Report 88
VERA 2015 and 2016 Geodetic Activities 92
Noto Station Status Report 95
Ny-Ålesund Geodetic Observatory 96
German Antarctic Receiving Station (GARS) O'Higgins 100
Onsala Space Observatory – IVS Network Station Activities during 2015–2016 104
Parkes Network Station Report 2015–2016 109
Shanghai Station Report for 2015–2016 110
The Helio-Geodynamic Testing Ground Area "Simeiz–Katsiveli": Some Results of the Observation Analysis 113
Svetloe Radio Astronomical Observatory 2015–2016 Report 116
Tsukuba 32-m VLBI Station 118
Nanshan IVS Biennial Report for 2015 and 2016 122
New Zealand VLBI Station, Warkworth 125
Westford Antenna 2015–2016 Biennial Report 128
Geodetic Observatory Wettzell – 20-m Radio Telescope and Twin Telescopes 131
Instituto Geográfico Nacional of Spain 136
Zelenchukskaya Radio Astronomical Observatory 2015–2016 Report 140

Operation Centers 143

Bonn Geodetic VLBI Operation Center 145
CORE Operation Center 2015 & 2016 Biennial Report 147
NEOS Operation Center 151

Correlators 153

The Bonn Astro/Geo Correlator 155
Haystack Observatory VLBI Correlator 2015–2016 Biennial Report 158
IAA Correlator Center Biennial Report 2015+2016 163
NICT Correlation Center 2015–2016 Biennial Report 166
Shanghai VLBI Correlator 169
Tsukuba VLBI Correlator 174
Washington Correlator 178

Data Centers 181

BKG Data Center 183
CDDIS Data Center Summary for the IVS 2015–2016 Biennial Report 185
Italy INAF Data Center Report 189
NICT Data Center Biennial Report for 2015–2016 190
Paris Observatory (OPAR) Data Center 192

Analysis Centers 195

Analysis Center of Saint Petersburg University .. 197
Geoscience Australia Analysis Center 2015-2016 Biennial Report 199
Report for 2015–2016 from the Bordeaux IVS Analysis Center 200
BKG/DGFI-TUM Combination Center Biennial Report 2015+2016 204
Matera CGS VLBI Analysis Center 209
DGFI-TUM Analysis Center Biennial Report 2015+2016 211
GFZ Analysis Center 2015/2016 Biennial Report 214
BKG/IGGB VLBI Analysis Center 219
GSFC VLBI Analysis Center Report 224
Haystack Observatory Analysis Center 229
IAA VLBI Analysis Center 2015–2016 Biennial Report 233
Italy INAF Analysis Center 236
KTU-GEOD IVS Analysis Center Biennial Report (2015–2016) 238
NICT VLBI Analysis Center Report for 2015–2016 241
Norwegian Mapping Authority Analysis Center Biennial Report 2015–2016 245
Paris Observatory (OPAR) Analysis Center 249
Onsala Space Observatory – IVS Analysis Center Activities during 2015–2016 252
Biennial Report (2015–2016) of PMD IVS Analysis Center 257
Pulkovo Observatory IVS Analysis Center (PUL) Report 2015–2016 262
SAI–VNIIFTRI VLBI Analysis Center 2015–2016 Report 266
IVS SHAO Analysis Center 2015–2016 Biennial Report 269
Tsukuba VLBI Analysis Center 272
U.S. Naval Observatory VLBI Analysis Center .. 276
USNO Analysis Center for Source Structure Report 278
Vienna Special Analysis Center Biennial Report 2015/2016 280

Technology Development Centers .. 285

Canadian VLBI Technology Development Center Report 287
GSFC IVS Technology Development Center Biennial Report Submission 288
MIT Haystack Observatory Technology Development Center 291
IAA Technology Development Center 2015—2016 Report 295
NICT Technology Development Center 2015+2016 Biennial Report 297
Onsala Space Observatory – IVS Technology Development Center Activities during 2015–2016 301
IGN Yebes Technology Development Center 306

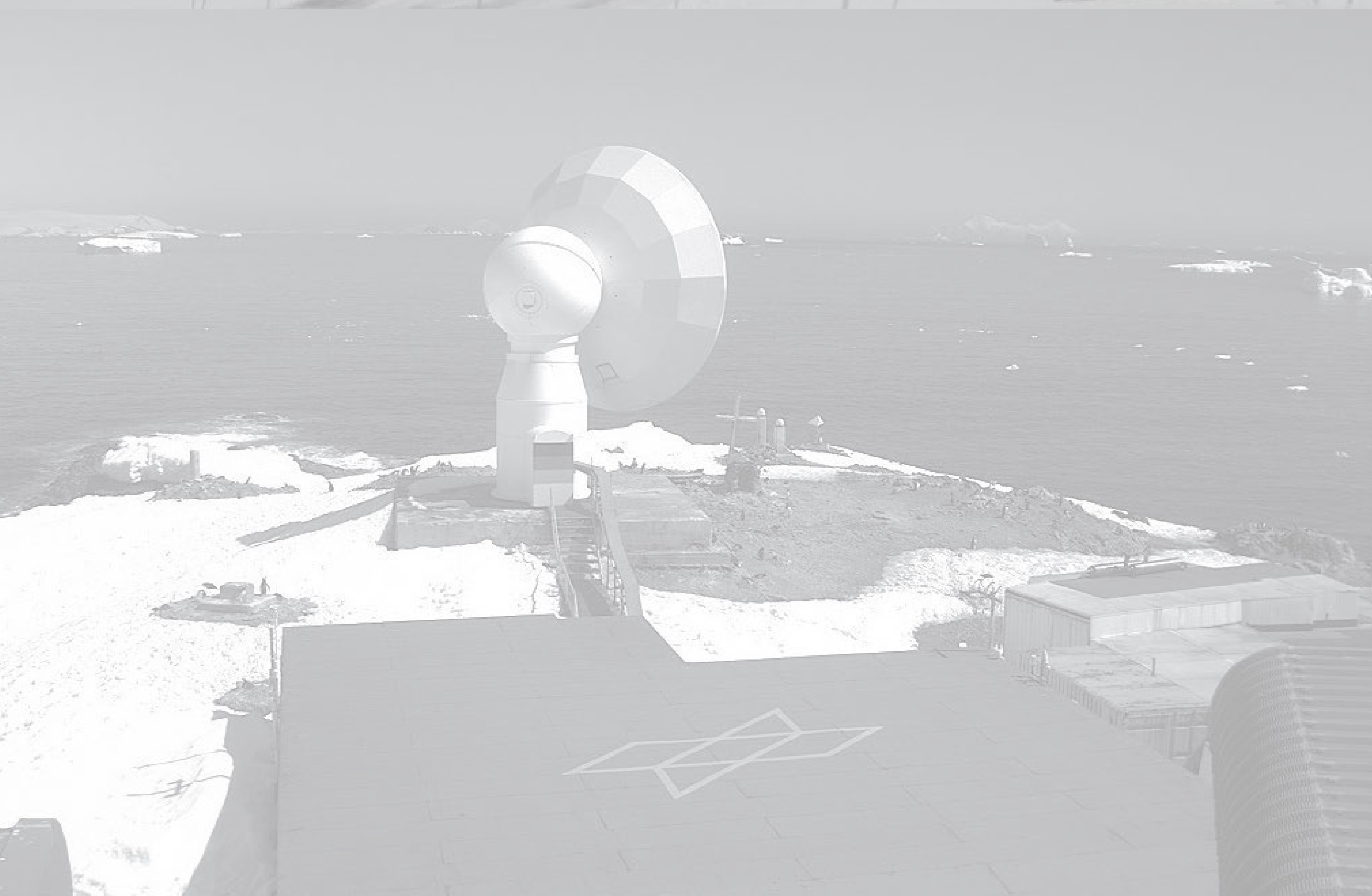
Bibliography 311

Bibliography 313

IVS Information 335

IVS Terms of Reference 337
Links to Additional IVS Information 344

About IVS



IVS Organization

Objectives

IVS is an international collaboration of organizations which operate or support Very Long Baseline Interferometry (VLBI) components. The goals are:

1. To provide a service to support geodetic, geophysical and astrometric research and operational activities.
2. To promote research and development activities in all aspects of the geodetic and astrometric VLBI technique.
3. To interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

The IVS

- Interacts closely with the IERS, which is tasked by IAU and IUGG with maintaining the international celestial and terrestrial reference frames (ICRF and ITRF),
- coordinates VLBI observing programs,
- sets performance standards for the observing stations,
- establishes conventions for data formats and products,
- issues recommendations for analysis software,
- sets standards for analysis documentation,
- institutes appropriate product delivery methods in order to insure suitable product quality and timeliness.

Realization And Status Of IVS

IVS consists of

- 32 Network Stations, acquiring high performance VLBI data,
- 3 Operation Centers, coordinating the activities of a network of Network Stations,
- 7 Correlators, processing the acquired data, providing feedback to the stations and providing processed data to analysts,
- 5 Data Centers, distributing products to users, providing storage and archiving functions,
- 28 Analysis Centers, analyzing the data and producing the results and products,
- 7 Technology Development Centers, developing new VLBI technology,
- 1 Coordinating Center, coordinating daily and long term activities.

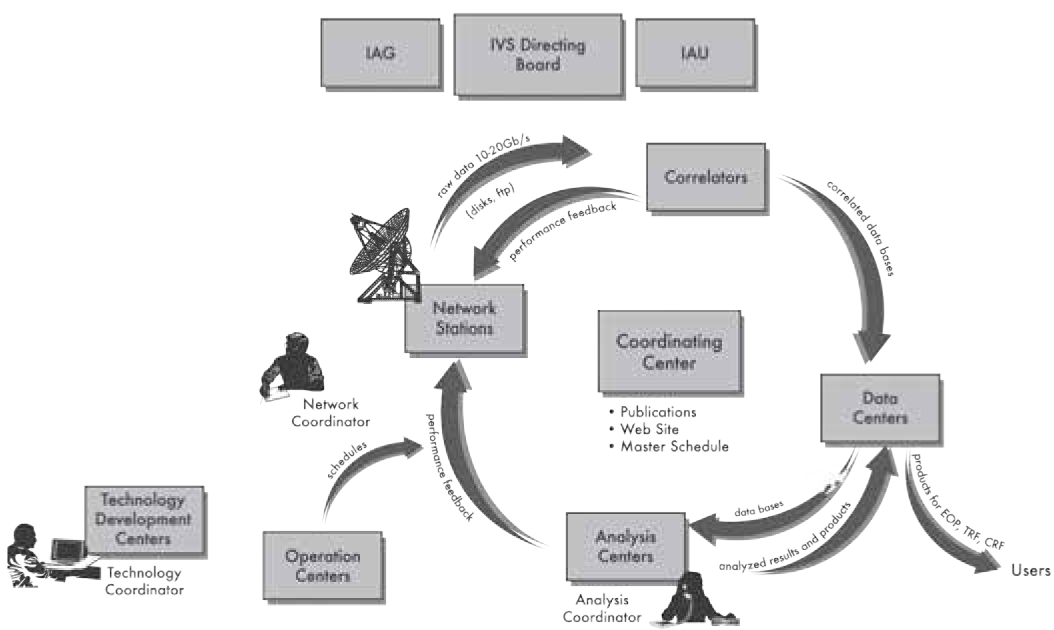
Altogether

- 83 Permanent Components, representing 41 institutions in 21 countries,
- ~300 Associate Members.

In addition the IVS has:

- Directing Board, determining policies, standards and goals; the board is composed of 16 members (elected and ex officio), including
- Coordinators for the network, analysis and technology.

ORGANIZATION OF INTERNATIONAL VLBI SERVICE



IVS Member Organizations

The following organizations contribute to IVS by supporting one or more IVS components. They are considered IVS Members. Listed alphabetically by country.

Organization	Country
Geoscience Australia	Australia
University of Tasmania	Australia
CSIRO	Australia
Vienna University of Technology	Austria
Centro de Rádio Astronomia e Aplicações Espaciais	Brazil
Geodetic Survey Division, Natural Resources Canada	Canada
Dominion Radio Astrophysical Observatory	Canada
Chinese Academy of Sciences	China
Finnish Geodetic Institute, Aalto University	Finland
Observatoire de Paris	France
Laboratoire d'Astrophysique de Bordeaux	France
Deutsches Geodätisches Forschungsinstitut	Germany
Bundesamt für Kartographie und Geodäsie	Germany
Institut für Geodäsie und Geoinformation der Universität Bonn	Germany
Forschungseinrichtung Satellitengeodäsie, TU-Munich	Germany
Max-Planck-Institut für Radioastronomie	Germany
GeoForschungsZentrum Potsdam	Germany
Istituto di Radioastronomia INAF	Italy
Agenzia Spaziale Italiana	Italy
Politecnico di Milano DIIAR	Italy
Geospatial Information Authority of Japan	Japan
National Institute of Information and Communications Technology	Japan
National Astronomical Observatory of Japan	Japan
National Institute of Polar Research	Japan
Auckland University of Technology	New Zealand
Norwegian Mapping Authority	Norway
Astronomical Institute of St.-Petersburg University	Russia
Institute of Applied Astronomy	Russia
Pulkovo Observatory	Russia
Sternberg Astronomical Institute of Moscow State University	Russia
Hartebeesthoek Radio Astronomy Observatory	South Africa
Korea Astronomy and Space Science Institute	South Korea
National Geographic Information Institute	S. Korea
Instituto Geográfico Nacional	Spain
Chalmers University of Technology	Sweden
Karadeniz Technical University	Turkey
Main Astronomical Observatory, National Academy of Sciences, Kiev	Ukraine
Laboratory of Radioastronomy of Crimean Astrophysical Observatory	Ukraine
NASA Goddard Space Flight Center	USA
U. S. Naval Observatory	USA
Jet Propulsion Laboratory	USA

IVS Affiliated Organizations

The following organizations cooperate with IVS on issues of common interest, but do not support an IVS component. Affiliated Organizations express an interest in establishing and maintaining a strong working association with IVS to mutual benefit. Listed alphabetically by country.

Organization	Country
Australian National University	Australia
University of New Brunswick	Canada
FÖMI Satellite Geodetic Observatory	Hungary
Joint Institute for VLBI in Europe (JIVE)	Netherlands
Westerbork Observatory	Netherlands
National Radio Astronomy Observatory	USA

Products

The VLBI technique contributes uniquely to

- Definition and realization of the International Celestial Reference Frame (ICRF)
- Monitoring of Universal Time (UT1) and length of day (LOD)
- Monitoring the coordinates of the celestial pole (nutation and precession)

Further significant products are

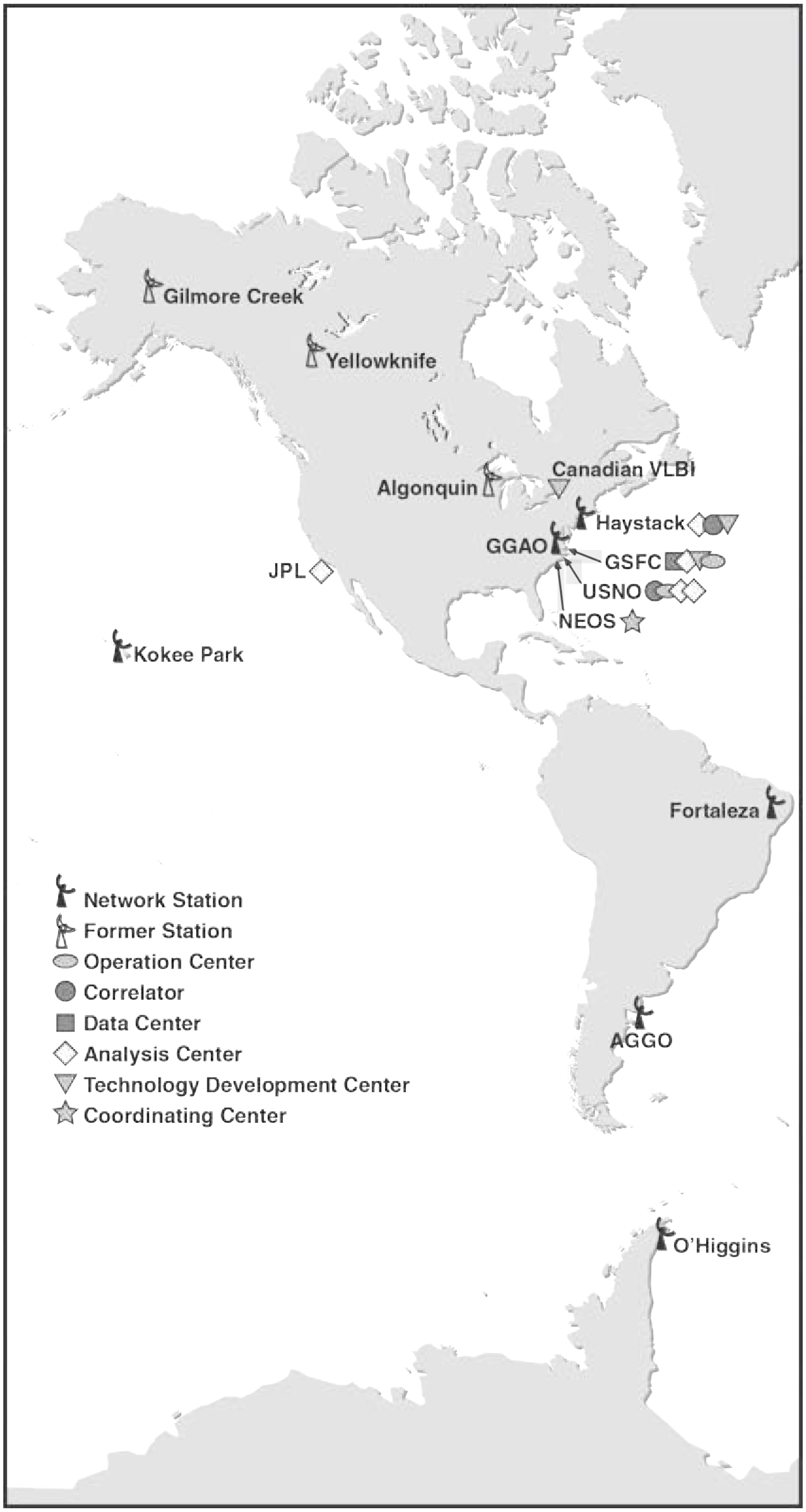
- All components of Earth Orientation Parameters at regular intervals
- Station coordinates and velocity vectors for the realization and maintenance of the International Terrestrial Reference Frame (ITRF)

All VLBI data and results in appropriate formats are archived in data centers and publicly available for research in related areas of geodesy, geophysics and astrometry.

IVS Component Map

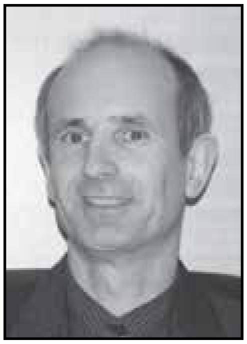
IVS Components by Country

Country	Qty.
Argentina	1
Australia	3
Austria	1
Brazil	1
Canada	1
China	4
Finland	1
France	3
Germany	10
Italy	7
Japan	12
New Zealand	1
Norway	2
Russia	9
South Africa	1
South Korea	2
Spain	2
Sweden	3
Turkey	1
Ukraine	2
USA	16
Total	**83**




Ny Ålesund
NMA
Metsähovi
Svetloe
Onsala
IAA
PUL
IGGB
Effelsberg
AIStPbU
SAI
BKG
GFZ
MAO
FGS(BKG,IGGB)
DGFI
Wettzell
Paris
TU Vienna
Zelenchukskaya
Bordeaux
INAF
Medicina
Simeiz
Yebes
KTU
PMD
Matera
Noto
Badary
Nanshan
Mizusawa
Tsukuba
Kashima 34
Sejong
Seshan
KASI
NICT
Shanghai
GSI
Kashima 11
Koganei
Katherine
Hartebeesthoek
Yarragadee
Parkes
GA
Warkworth
Hobart
Syowa

IVS Directing Board

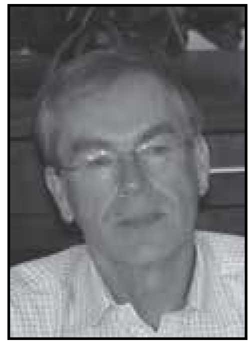


NAME: Axel Nothnagel

AFFILIATION: University of Bonn, Germany

POSITION: Chair, Analysis and Data Centers Representative

TERM: Feb 2013 to Feb 2017



NAME: Ludwig Combrinck

AFFILIATION: Hartebeesthoek RAO, South Africa

POSITION: IAG Representative

TERM: ex officio

NAME: Dirk Behrend

AFFILIATION: NVI, Inc./Goddard Space Flight Center, USA

POSITION: Coordinating Center Director

TERM: ex officio

NAME: John Gipson

AFFILIATION: NVI, Inc./Goddard Space Flight Center, USA

POSITION: Analysis Coordinator

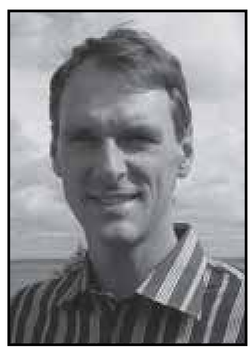
TERM: permanent

NAME: Alessandra Bertarini

AFFILIATION: University of Bonn, Germany

POSITION: Correlators and Operation Centers Representative

TERM: Feb 2015 to Feb 2019



NAME: Rüdiger Haas

AFFILIATION: Chalmers University of Technology, Sweden

POSITION: Technology Development Centers Representative

TERM: Feb 2013 to Feb 2017

NAME: Patrick Charlot

AFFILIATION:Laboratoire d'Astrophysique de Bordeaux, France

POSITION: IAU Representative

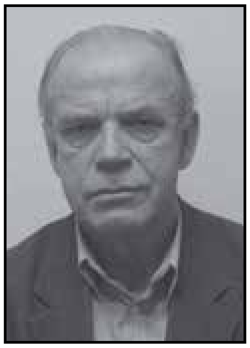
TERM: ex officio

NAME: Ed Himwich

AFFILIATION: NVI, Inc./Goddard Space Flight Center, USA

POSITION: Network Coordinator

TERM: permanent

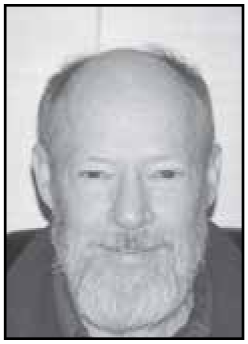


NAME: Alexander Ipatov

AFFILIATION: Institute of Applied Astronomy, Russia

POSITION: At Large Member

TERM: Feb 2015 to Feb 2017



NAME: Arthur Niell

AFFILIATION: MIT Haystack Observatory, USA

POSITION: Analysis and Data Centers Representative

TERM: Feb 2015 to Feb 2019

NAME: Ryoji Kawabata

AFFILIATION: Geospatial Information Authority, Japan

POSITION: At Large Member

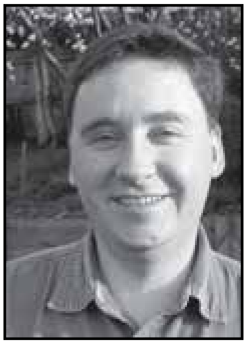
TERM: Feb 2015 to Feb 2017

NAME: Torben Schüler

AFFILIATION: Bundesamt für Kartographie und Geodäsie, Germany

POSITION: Networks Representative

TERM: Feb 2015 to Feb 2019

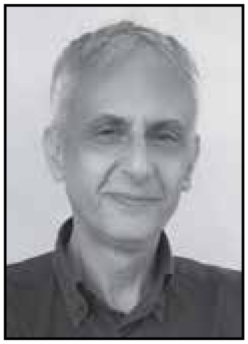


NAME: James Lovell

AFFILIATION: University of Tasmania, Australia

POSITION: Networks Representative

TERM: Feb 2013 to Feb 2017



NAME: Gino Tuccari

AFFILIATION: Istituto di Radioastronomia, INAF, Italy

POSITION: Technology Coordinator

TERM: permanent

NAME: Chopo Ma

AFFILIATION: NASA Goddard Space Flight Center, USA

POSITION: IERS Representative

TERM: ex officio

NAME: Guangli Wang

AFFILIATION: Shanghai Astronomical Observatory, China

POSITION: At Large Member

TERM: Feb 2015 to Feb 2017

IVS Chair's Report

Axel Nothnagel

Institute of Geodesy and Geoinformation of the University of Bonn

The years 2015 and 2016 have brought again a number of new developments and achievements for the IVS as well as for the global geodetic and astrometric communities of which we are integral parts. Most of them are documented in this biennial report, but I am sure that many activities go unnoticed although their implications are far-reaching and will only be visible in the broader picture of the IVS. Writing contributions to this report may be seen as an unnecessary and time-consuming burden, but the effort is worthwhile in the long run. The reports—both the online and in particular the printed versions in many bookshelves—have always been a valuable source of information ready at hand even for the authors themselves. To reduce work and costs, the IVS Directing Board decided to change to a two-year rhythm for the reports. We hope that through this decision the reports have become livelier and will also increase the readers' interest. I would like to thank all the authors for their efforts to produce their contributions in due time for an up-to-date publication. This goes together with my appreciation for the editors Karen Baver, Dirk Behrend, and Kyla Armstrong, who make all this happen in time and with high quality. I would also like to thank the NASA Goddard Space Flight Center VLBI project, which funds the personnel and bears the printing costs within their IVS Coordinating Center commitment.

Turning to the achievements in the reporting period, I would like to start with the "Strategic Plan of the IVS for the Period 2016–2025." It has taken some efforts to prepare this document including a retreat of the IVS Directing Board with high-ranking guests and plenty of email exchange. In the end, a noteworthy document was published on the IVS Web site giving us a very valuable guideline for all activities at hand. Since many developments are in constant flow, updates will have to be discussed in the IVS Directing Board and elsewhere in appropriate intervals.

Another noteworthy event was the adoption of the resolution "Global Geodetic Reference Frame for Sustainable Development (GGRF)" (No. A/69/L.53) by the General Assembly of the United Nations on February 26, 2015. As the official press release says, it is "… the first resolution recognizing the importance of a globally-coordinated approach to geodesy – the discipline focused on accurately measuring the shape, rotation and gravitational field of planet Earth." This is an important step forward in making politicians and the public aware of geodesy in general and the space-geodetic techniques (such as VLBI) in particular.

In the months following the resolution, a working group of the UN Global Geospatial Information Management (UN-GGIM) on "Global Geodetic Reference Frame" (GGRF WG) worked on a roadmap for the realization of the UN resolution. The GGRF Roadmap is divided into five themes: 1) Geodetic Infrastructure; 2) Data Sharing, Policies, Standards and Conventions; 3) Education Training and Capacity Building; 4) Communication and Outreach; and 5) Governance. Within these themes, recommendations are prepared of how the goals of the GGRF can be reached. VLBI is mentioned explicitly under infrastructure. In a session of the UN-GGIM on August 3–5, 2016, the GGRF working group was granted the status of a permanent sub-commission and the GGRF Roadmap was adopted.

Although the IVS is not involved directly in these processes, we certainly have to follow their developments. On the other hand, input was provided by the IVS in the form of text elements on certain conceptual topics. It remains to be seen how fruitful they are and how they find their way into GGRF documents. In any case, the GGRF activities should be seen as a concerted effort to raise awareness for our work and, hopefully, this will be of benefit to our community eventually.

Turning back to the IVS activities, many organizational, technical, and scientific meetings of the IVS and its components took place in the last two years. You may understand that I can mention only a few of them.

In May 2015, the 21st Meeting of the European VLBI Group for Geodesy and Astrometry (EVGA) was held at Ponta Delgada on the Azores Islands (Portugal). As part of this meeting the Santa Maria VGOS telescope was officially inaugurated with a festive celebration. For this purpose almost 100 attendants of the EVGA meeting were shuttled by plane from São Miguel Island to the neighboring island of Santa Maria. This must have been an enormous logistical effort and we still thank the organizers for their organizational and financial efforts to make this unforgettable event happen.

A day later we also celebrated the official inauguration of the Badary and Zelenchukskaya VGOS telescopes. A live stream was organized to the headquarters of the Institute of Applied Astronomy in St. Petersburg, Russia, where the attendants of the EVGA meeting could congratulate our Russian colleagues online.

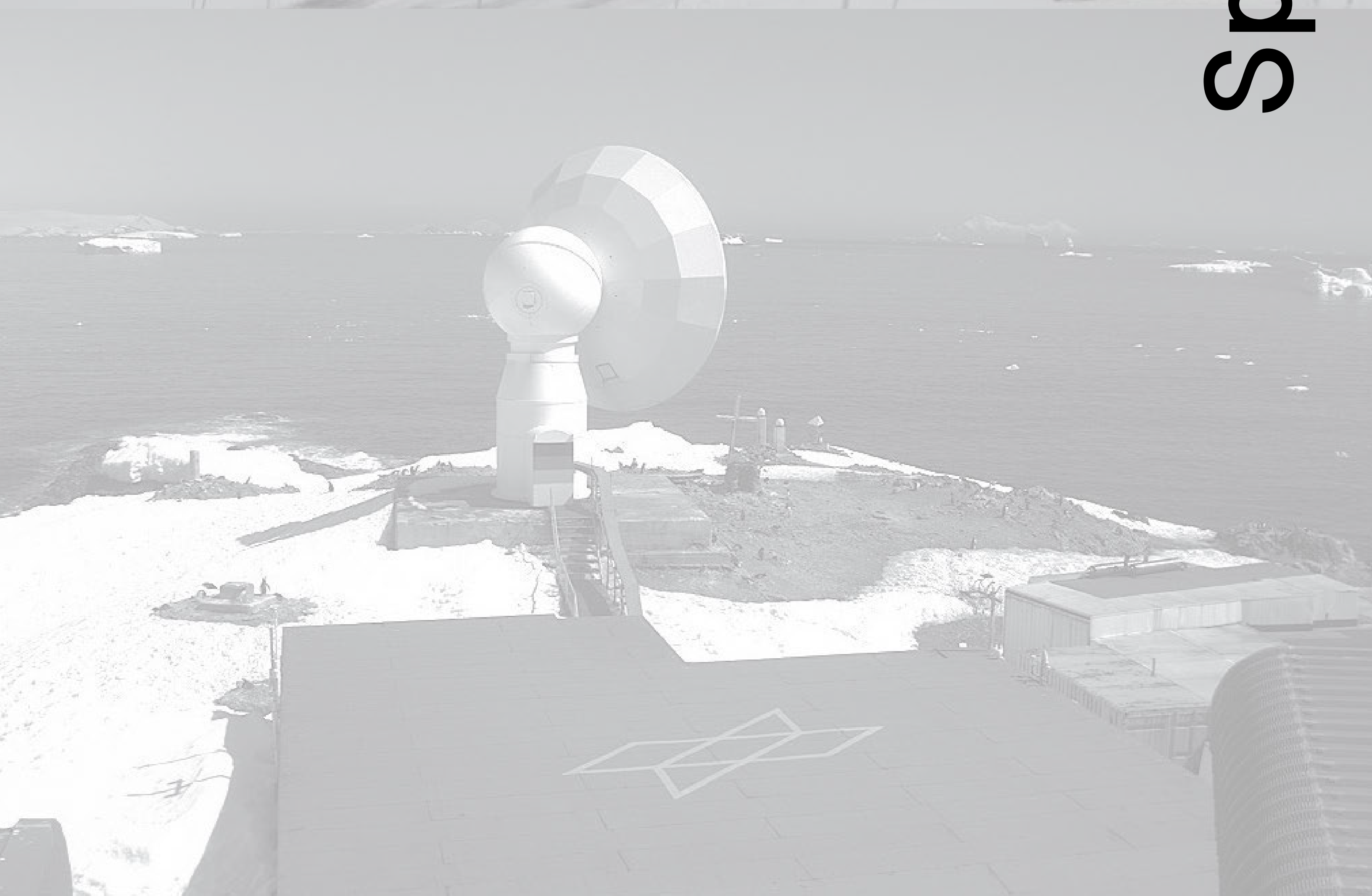
In March 2016, the Second VLBI Training School was organized by Rüdiger Haas and the IVS Committee on Education and Training together with Aletha de Witt and her colleagues of the Hartebeesthoek Radio Astronomy Observatory (HartRAO). Thirty-one young researchers with a great share from African countries (19) attended and learned a lot about geodetic and astrometric VLBI. Rüdiger had invited a number of knowledgeable speakers on all facets of planning, observing, correlation, and analysis of VLBI sessions. Hands-on tutorials were highly appreciated by the attendants. These were prepared by the teachers and often by HartRAO technical and scientific personnel, in particular by Jonathan Quick and Roelf Botha.

Immediately following, the 9th IVS General Meeting was hosted by Ludwig Combrinck and his colleagues of HartRAO. Many interesting developments and achievements were presented, but equally important were the numerous opportunities to exchange ideas and discuss solutions. The hosts organized the conference very well in a splendid location and a framework of splinter meetings and social gatherings showing us the African culture. Even the Minister of Science and Technology of South Africa, Mrs. Naledi Pandor, gave us the honor of attending the opening ceremony and delivering a welcome speech. Also notable in the many days of the event was the ground breaking ceremony of the new VGOS telescope close to the existing 26-m and 15-m telescopes. We look forward to the first observations and a successful operational phase.

The IVS Directing Board (DB) met several times in the reporting period, first on the Azores (May 22, 2015), then in conjunction with the DB Retreat in Penticton, BC, Canada (October 9, 2015), at HartRAO (March 19, 2016), and at MIT Haystack Observatory (October 15, 2016). In all these meetings a number of general decisions were taken. Summaries are available on the IVS Web page under Directing Board.

In summary, the last two years have again been a very fruitful and successful time for the IVS. Please read this report which will give you a detailed insight into the activities of the various IVS components.

Special Reports



Task Force on IVS Intensives

Updated Final Report

Rüdiger Haas – for the Task Force on IVS Intensives

Abstract In 2010, the IVS set up a task force to study the Intensive sessions with the goal of evaluating the Intensives and suggesting ways to improve them. The task force presented its final report to the IVS Directing Board in May 2017. This report consisted of a review of recent IVS Intensive research and recommendations for future improvement of the Intensives. The report is now being presented to the IVS in general as a special report in the 2015+2016 Biennial Report. At the same time, the opportunity was taken to update the report with the addition of information about VGOS INT01 preparations, new information about source constellation influence (spatial sky coverage) and temporal coverage, and related references. It should be noted that the reporting of research efforts within the IVS community is not exhaustive; instead major trends are covered.

1 Introduction

At its 23rd Directing Board (DB) meeting, held on 12 February 2010 at the University of Tasmania in Hobart, the IVS DB created the *Task Force on IVS Intensives*. The initial members of this task force were Rüdiger Haas (chair), Axel Nothnagel, Kerry Kingham, Brian Luzum, Dirk Behrend, Shinobu Kurihara, Thomas Hobiger, Minttu Uunila, and Zinovy Malkin. During later years, some of the members left the task force because of retirement or change of job.

The initial idea of the task force was to study various aspects of the Intensive (INT) sessions, with the overriding goal of improving the INT results. The objective of the INT sessions is to provide highly accurate and low latency UT1 results. However, the problem is that the INT sessions still do not live up to these expectations and unfortunately do not provide the expected precision and accuracy of UT1, and that the latency still could be improved. For example, Baver et al. (2012) reported RMS differences w.r.t. the IERS C04 series on the order of 25 μs for INT1 in 2011. Malkin (2013) gave RMS values w.r.t. IERS C04 of 18.0, 9.9 and 18.5 μs for INT1 (2005–2011), INT2 (2005–2011), and INT3 (2007–2011), respectively. In contrast to this, IVS network sessions provide RMS values that are better than the INTs by a factor of 3 to 4.

Topics of the task force were to study potential ways to improve the INT results. A proposal for a unified analysis strategy for INT should be developed, including a strategy for three levels of INT products. The three level INT products were meant to be based on the latency of the UT1 results, i.e., Ultra-rapid UT1, rapid UT1, and final UT1.

Numerous studies concerning the INTs were performed during the past years in the IVS community. The efforts can be separated into two main categories. The first category covers scheduling and operations of INT sessions, while the second category covers modeling and analysis. This report covers major trends, instead of providing an exhaustive description of all research efforts within the community. For brevity, the bibliography only lists an author or group's latest pa-

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IVS 2015+2016 Biennial Report

per about a research activity, except where an earlier paper is useful to support the discussion of the activity.

2 Scheduling and operational aspects

2.1 Source constellation influence (spatial sky coverage)

Baver et al. (2004) noted a link between better sky coverage and lower UT1 formal errors. Gipson and Baver (2016a) reported the expansion of the INT01 scheduling source list from ~30 strong but unevenly distributed sources to all geodetic sources that are mutually visible at Kokee Park and Wettzell. This "maximal source strategy" was first tested in ten 2009 and 2010 IVS R&Ds, and it was adopted for all INT01 scheduling in summer 2016.

But using all mutually visible sources weakens the source set, so Baver and Gipson (2014) studied source sets with intermediate numbers of sources to balance source strength and sky coverage. They are testing a balanced source set in six 2016 and 2017 IVS R&Ds.

Other studies examined the areas of the sky that affect the UT1 formal error with more precision. Uunila et al. (2013) divided the area of mutual visibility between Wettzell and Kokee Park into six sections and analyzed INT sessions. They revealed that coverage of the corners of the mutual visibility area is important for obtaining small UT1 formal errors. Gipson and Baver (2015) used a minimization algorithm to determine the ideal distribution of observations. Their best case indicated that UT1 formal errors are minimized when observations are only made within each mutual visibility corner.

2.2 Observation order (temporal sky coverage)

Temporal coverage is the degree of repeated observing in areas of the sky throughout a schedule due to observation order. Baver et al. (2012) examined observed INT01 sessions and reported that good temporal coverage, especially near the centers of Kokee Park's and Wettzell's northeast and northwest quadrants, reduces sensitivity to atmospheric turbulence (the RMS about the mean of the UT1 estimates from a series of solutions into which random noise is introduced). Baver and Gipson (2013) used schedule simulations to show that atmospheric turbulence sensitivity is reduced by cycling evenly through observations in Kokee Park's and Wettzell's northeast quadrant, northwest quadrant and center (near azimuth 0°), instead of observing for a while in first one of these areas, then a second area, and finally the third area. The even cycling also reduced the unscaled UT1 formal error of a representative schedule from 23.5 μs to 10.3 μs.

2.3 Impact factor analysis

Leek et al. (2015) studied the use of so-called "impact factors" (IF) to identify the most influential observations to optimize the determination of the target parameters of a geodetic VLBI session. They show that the IF-strategy is superior to standard scheduling for INTs during 2009 through 2013. The IF-strategy is also applicable to schedule networks with twin telescopes. Networks with twin telescopes instead of single telescopes proved to lead to an improvement of about 50% in the formal errors of UT1.

2.4 Tag-along stations in INTs

Kareinen et al. (2017) showed that the inclusion of a third station in tag-along mode has the potential to improve the INT1 and INT2 results by up to 33%. This study was based on a complete year of INT1 and INT2 schedules and used full end-to-end simulations with a realistic error model including station specific atmospheric turbulence.

2.5 Dedicated ultra-rapid sessions

The goal to achieve UT1 with low latency was already addressed in 2007 in a Japanese-European collaboration. Periodically, dedicated INT sessions were scheduled and the observational data sent electronically to the Tsukuba correlator, where the data were correlated and analyzed and near real-time UT1 was derived, see Sekido et al. (2008). Very low latency was achieved (Matsuzaka et al., 2008) with results on the same accuracy level as the standard INT sessions (Haas et al., 2010; Koyama et al., 2010). As a result, the ultra-rapid strategy was adopted in 2009 for the regular VLBI intensive series INT2, which in turn led to improved UT1 predictions (Luzum and Nothnagel, 2010).

2.6 Ultra-rapid UT1 during normal 24-h IVS sessions

Matsusaka et al. (2010) showed that it also is possible to determine ultra-rapid UT1 results during ongoing standard 24-h long IVS sessions. Standard IVS sessions that included Onsala and Tsukuba (e.g., R1, R&D) were used and the observational data from Onsala were e-transferred in real-time to Tsukuba, where the data were correlated and analyzed, providing UT1 results already during the ongoing IVS session. However, since the 24-h IVS schedules are optimized for network observations and not for UT1 determination on just one baseline, a special analysis strategy had to be developed. Sliding-window approaches were applied using either a fixed number of observations (e.g., 35) or a fixed time interval (e.g., 3-h) with delay observations for the analysis. This strategy was then also applied to the two continuous VLBI campaigns CONT11 an CONT14. Haas et al. (2017) showed that the accuracies from the CONT ultra-rapid single baseline operations are roughly a factor of three worse than the results from both dedicated one-baseline sessions and/or the complete analysis of network sessions.

2.7 INT sessions with 2-h duration observations

Artz et al. (2012) investigated the impact of observation time on the results from INT sessions. A series of R&D INT sessions with 2-hour duration showed that the formal errors of UT1 decreased by a factor of $\sqrt{2}$, when compared to INTs with 1-hour duration, and that the agreement w.r.t. UT1 results from 24-h sessions improved by about 15%.

2.8 VGOS INT01 scheduling

Baver and Gipson (2017) used simulations to examine source catalogs and *Sked* file parameters in order to develop a proposed VGOS INT01 schedule file configuration. The configuration reduced the average UT1 formal error from 7.7 μs to 3.4 μs. But the configuration should be retested once the Kokee 12-m antenna's horizon mask is finalized.

3 Modeling and analysis aspects

3.1 Impact of ocean loading

The general importance of ocean loading on the determination of earth rotation derived from VLBI was shown by Scherneck and Haas (1999). For network sessions, impacts of up to 3 μs on UT1 were detected when testing different ocean loading models. It can be assumed that INT sessions with just 2 or 3 stations are affected in a similar way.

3.2 Impact of atmospheric loading

Uunila et al. (2012) tested using atmospheric loading for the analysis of INT sessions. However, they investigated this in connection to testing different mapping functions. They could not detect any significant difference larger than 0.01 μs on UT1 and could not identify whether this was due to the mapping function or the atmospheric loading.

3.3 Impact of seasonal station motion

Malkin (2013) investigated the impact of seasonal station motions on UT1 estimates from INT sessions. It was found that neglecting seasonal station motion affects, e.g., the INT1 series by more than 1 μs.

3.4 Impact of mapping functions

Kareinen et al. (2015) investigated the impact of mapping functions on the INT results. They tested the Global Mapping functions (GMF) versus the Vienna Mapping Functions (VMF1) and could not detect any significant difference larger than 1 μs on the accuracy of UT1.

3.5 Impact of a priori zenith troposphere delays

Teke et al. (2015) used zenith troposphere delays from GNSS processing and introduced these in the analysis of INT sessions. They did not find any significant impact on the corresponding UT1 results.

3.6 Impact of a priori gradient modeling

Böhm et al. (2010) used external gradient information based on raytracing for the analysis of INT2 sessions. They found changes of the estimated UT1 values on the order of 10 μs.

Teke et al. (2015) used horizontal total gradients estimated from GNSS observations and used these as a priori values for the analysis of several years of INT sessions. They converted the UT1 results to LOD and compared these to GNSS results for LOD. A slight improvement of agreement on the order of 1 μs was found for INT1 and INT2.

Gipson and Baver (2016b) used a priori gradient information based on the analysis of R1 and R4 sessions and applied it to the analysis of INT01 sessions. They found changes of UT1 estimates about 7.5 μs and a slight improvement on the order of less than 1 μs when compared to results from 24-h sessions.

3.7 Impact of raytraced a priori delays

Madzak et al. (2012) used raytraced delays as a priori values for the data analysis of INT sessions and converted the derived UT1 values to LOD. They found that the agreement of INT2 and INT3 sessions improved by more than 1 μs while there was no effect, neither positive nor negative, on the INT1 sessions.

3.8 Impact of locally measured pressure and cable calibration data

Kareinen et al. (2015) investigated the impact of local station data, i.e., locally measured atmospheric pressure and cable calibration data, on the accuracy of UT1 from INT sessions. They found an insignificant effect of less than 0.01 μs whether using locally measured data, or not. This required of course that the cable data were reliable and free of outliers.

3.9 Impact of a priori polar motion and UT1

Nothnagel and Schnell (2008) investigated the impact of a priori polar motion (and nutation) on UT1 derived from INT sessions from a theoretical point of view. They found a directly proportional effect with maximum values of up to 30 μs per milliarcsecond offset in polar motion (or nutation). This highlights the importance of accurate a priori polar motion.

Nilsson et al. (2015) used a Kalman Filter approach to make use of external information of polar motion and LOD from GNSS provided as IGS rapid products in the analysis of five years of INT sessions. They found a significant reduction of the WRMS differences w.r.t. UT1 results derived from IVS 24-h sessions, both from using polar motion and/or LOD separately. The largest reduction was achieved when using both polar motion and LOD.

Kareinen et al. (2015) investigated the impact of a priori polar motion values used in the analysis of INT sessions on the accuracy of the derived UT1 results. They found that the a priori polar motion data must not be older than 12 hours to achieve UT1 accuracy of better than 20 μs. To guarantee less than 5% degradation for the UT1 accuracy, the a priori polar motion must not be older than 6 hours.

3.10 Impact of a priori nutation

As mentioned earlier, Nothnagel and Schnell (2008) investigated the impact of a priori nutation (and polar motion) on UT1 derived from INT sessions from a theoretical point of view. They found a directly proportional effect with maximum values of up to 30 μs per milliarcsecond offset in nutation (and polar motion), which is significant since even state-of-the-art nutation models show deviations of as much as one milliarcsecond.

3.11 Impact of free core nutation

Malkin (2011) studied the impact of celestial pole offsets (CPO) on the accuracy of UT1 estimates. The CPO are corrections to the IAU 2000/2006 models for precession and nutation and are attributed to errors in precession and/or very low frequency nutation terms, as well as the free core nutation (FCN). There are only empirically determined models of CPO. Using these models in the analysis of INT sessions has an impact on the order of 1.4 μs.

Gipson and Baver (2016b) studied this effect further and found an impact of less than 1 μs.

3.12 Automated analysis of INT sessions

A fully automated way to analyse INT sessions was developed by Kareinen et al. (2015). It starts with the version-1 databases in S- and X-band and works completely automatically without any human interaction. Ambiguity resolution and ionospheric calibration are included in this analysis.

3.13 Robust estimators for the analysis of INT sessions

Kareinen et al. (2016) implemented an algorithm to automatically resolve the ambiguities in geodetic VLBI data using robust estimation with the L1-norm. The results of this study show that the L1-norm is better at automatically resolving the ambiguities than the L2-norm. The increase in the number of successfully analyzed INT sessions was 5% when using L1-norm instead of L2-norm, accompanied by smaller post-fit residuals in the final UT1 estimation step.

4 Recommendations

The conclusions from the studies in the IVS community concerning the INTs cover three main aspects, which are 1) scheduling, 2) a unified modeling and analysis strategy, and 3) INT products with three levels of latency and accuracy.

4.1 Scheduling

We encourage to continue studies concerning optimized scheduling of INT sessions. There are a number of promising approaches, e.g., impact factors and maximal source strategy, but also adding further stations to the INTs, which might lead to improved accuracy. However, with the upcoming VGOS network and corresponding operations, one general question is whether INTs in their current form will continue to exist in the near future at all (Nothnagel et al., 2016).

4.2 Unified modeling and analysis strategy

As a unified modeling and analysis strategy for INT sessions we propose to model all known effects that have been shown to significantly impact the accuracy of INT results. This will also be of importance for future VGOS observations. We propose to:

1. use the most recent reference frames, i.e. currently ICRF2 and ITRF2014, including seasonal station modeling.
2. use the most recent IAU models for precession and nutation.
3. use empirical FCN models.
4. use recent mapping functions (MF), however adapted to the different INT products (see next sub-section) according to the availability of the MF information. For example, GMF(GPT2) should

be for near real-time analyses, but VMF1 for post-processing, final INT analyses.
5. use a priori gradients, however adapted to the different INT products (see next sub-section) according to the availability of the gradient information. For example, gradients from numerical weather model (NWM) predictions should be used for near real-time analyses, while gradients from GNSS analyses and/or post-processed final NWM should be used for post-processing, final INT analyses.
6. use the most recent ocean loading modeling.
7. use atmospheric loading.
8. use cable-calibration data, at least for post-processing analyses.

4.3 Three-level INT products

We propose to strive for INT products on three levels, mainly distinguished by their latency and accuracy. These can be classified as products from "ultra-rapid", "rapid" and "final" analyses. This fits also into the strategic plan of the IVS for the VGOS era (Nothnagel et al., 2016).

4.3.1 Ultra-rapid analysis

This INT product should make use of real-time data streaming, near real-time correlation, and near real-time automated data analysis (no human interaction), in order to achieve the lowest possible latency. The goal is to achieve a latency below 1-hour after the INT session. One dedicated IVS analysis center (AC) could have the responsibility for these products. However, higher robustness would of course be achieved with several ACs taking care of this. The results should be delivered as eopi-files to the IVS and IERS.

4.3.2 Rapid analysis

The rapid analysis can be performed based on the data bases produced in ultra-rapid mode. However, there should be human interaction to check the processing and guarantee quality of the results. This work could be done by one AC only and eopi-files could be delivered to the IVS and IERS with low latency, i.e. within 3 hours after the INT session. However, higher robustness would of course be achieved with several ACs taking care of this.

4.3.3 Final analysis

The final analysis should be based on a combination of unconstrained normal equations from several ACs via SINEX files. It was shown by Böckmann et al. (2010) that such an approach is suitable for the combination of analyses performed by several ACs and leads to better accuracy than each of the individual solutions itself. The latency of this INT product is expected to be lower, e.g., within one week after the INT session.

In any case, all analyses included in the three levels of INT processing should follow a unified analysis strategy, see the previous sub-section.

Acknowledgements

We gratefully acknowledge the work of the IVS community performed during the past years on the topic of IVS INTs.

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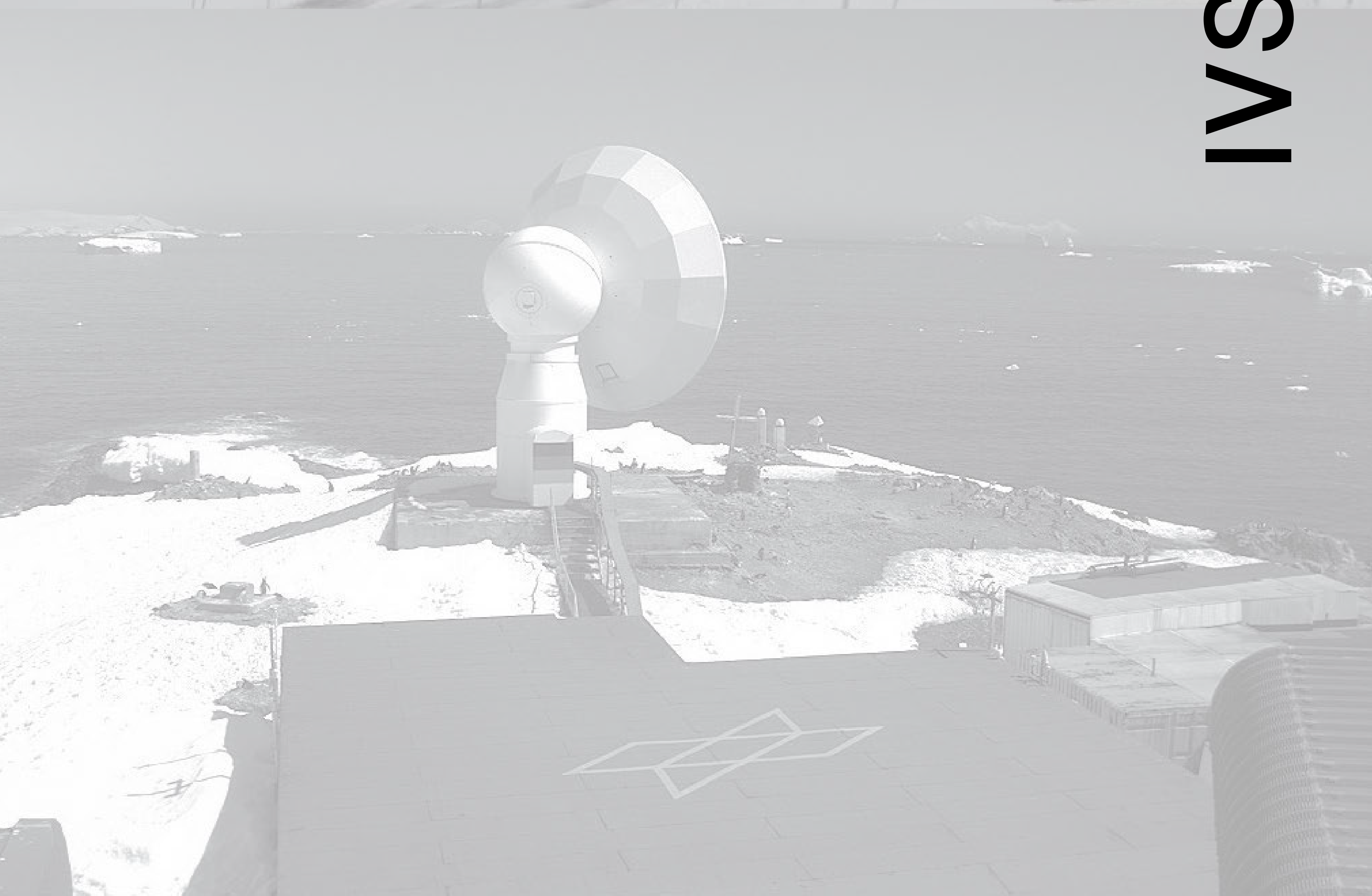
IVS Coordination



Coordinating Center Report

Dirk Behrend

Abstract This report summarizes the activities of the IVS Coordinating Center during the calendar years 2015 and 2016 and provides an outlook on activities planned for the next two years.

1 Coordinating Center Operation

The IVS Coordinating Center is based at the Goddard Space Flight Center and is operated by NEOS (National Earth Orientation Service), a joint effort for VLBI by the U.S. Naval Observatory and the NASA Goddard Space Flight Center.

The mission of the Coordinating Center is to provide communications and information for the IVS community and the greater scientific community and to coordinate the day-to-day and long-term activities of IVS.

The Web server for the Coordinating Center is provided by Goddard. The address is

`http://ivscc.gsfc.nasa.gov`.

2 Activities during 2015 and 2016

During the period from January 2015 through December 2016, the Coordinating Center supported the following IVS activities:

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IVS 2015+2016 Biennial Report

- **Directing Board support:** Coordinated, with local committees, four IVS Directing Board meetings: Ponta Delgada, Azores, Portugal (May 2015); Penticton, BC, Canada (October 2015); Johannesburg, South Africa (March 2016), and Westford, MA, USA (October 2016). Notes from each meeting were published on the IVS Web site.
- **VGOS:** Supported the activities for establishing the VLBI Global Observing System (VGOS) through participation in the VGOS Technical Committee (VTC) and the VGOS Project Executive Group (VPEG).
- **Communications support:** Maintained the Web pages, e-mail lists, and Web-based mail archive files. Maintained the 24-hour and Intensive session Web pages including the data acquisition, correlation, analysis, and performance summaries.
- **Meetings:** Coordinated, with the Local Committees, the eighth IVS Technical Operations Workshop, held at Haystack Observatory in May 2015, and the ninth IVS General Meeting, held at Eku-

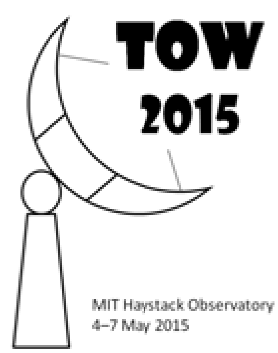

Fig. 1 Logo of the eighth IVS Technical Operations Workshop.

Fig. 2 Logo of the ninth IVS General Meeting in South Africa.

deni (Johannesburg), South Africa in March 2016. Chaired the Program Committees of both meetings.

- **IVS Retreat:** Supported the organization of the IVS Retreat held at DRAO (Dominion Radio Astrophysical Observatory), Penticton, BC, Canada on October 7–8, 2015. The participants (IVS Directing Board plus six invited guests) discussed the current and future challenges for the IVS based on an evaluation of the current state. The resulting Strategic Plan 2016–2025 was posted on the IVS Web site and is also contained in the Proceedings volume of the ninth IVS General Meeting.

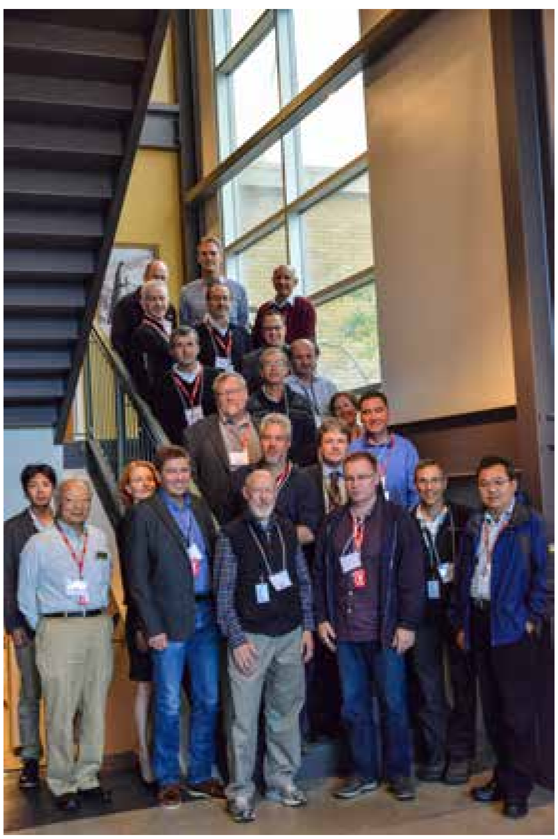

Fig. 3 Participants of the IVS Retreat in Penticton.

- **Publications:** Published the 2014 Annual Report in summer 2015. Published six editions of the IVS Newsletter in the months of April, August, and December of 2015 and 2016. Published the Proceedings volume of the ninth IVS General Meeting in December 2016. All publications are available electronically as well as in print form.
- **Observing Program Committee (OPC):** Coordinated meetings of the OPC to monitor the observing program, review problems and issues, and discuss changes.
- **Master Schedules for 2015 and 2016:** Generated and maintained the Master Observing Schedules for 2015 and 2016. Coordinated VLBI resources for observing time, correlator usage, and disk modules. Coordinated the usage of Mark 5 systems at IVS stations and efficient deployment of disk modules.
- **2017 Master Schedule:** Generated the proposed Master Schedule for 2017 and received approval from the Observing Program Committee.

3 Staff

The staff of the Coordinating Center is drawn from individuals who work at Goddard. The staff and their responsibilities are listed in Table 1.

Table 1 IVS Coordinating Center staff.

Name	Title	Responsibilities
Dirk Behrend	Director	Web site and e-mail system maintenance, Directing Board support, meetings, publications, session Web page monitoring
Cynthia Thomas	Operation Manager	Master schedules (current year), resource management and monitoring, meeting and travel support, special sessions
Frank Gomez	Web Manager	Web server administration, mail system maintenance, Data Center support, session processing scripts, mirror site liaison
Karen Baver	General Programmer and Editor	Publication processing programs, LaTeX support and editing, session Web page support and scripts, Data Center support
Kyla Armstrong	Data Technician and Editor	Publications support and Web site support

4 Plans for 2017 and 2018

The Coordinating Center plans for 2017 and 2018 include the following:

- Maintain IVS Web site and e-mail system.
- Publish the 2015+2016 Biennial Report (this volume).
- Coordinate, with the local committee, the ninth IVS Technical Operations Workshop to be held at the MIT Haystack Observatory, MA, USA in May 2017.
- Coordinate, with the local committee, the tenth IVS General Meeting to be held in Longyearbyen, Spitsbergen, Norway in June 2018.
- Publish the Proceedings volume of the tenth IVS General Meeting.
- Support Directing Board meetings in 2017 and 2018.
- Coordinate the 2017 and 2018 Master Observing Schedules and IVS resources.
- Publish Newsletter issues in April, August, and December.
- Support the VGOS activities within the VTC and the VPEG.

Analysis Coordinator Report

John Gipson

Abstract I summarize some of the important issues related to IVS analysis that have surfaced over the last two years.

1 Analysis Comments

The Goddard VLBI group has the responsibility to analyze specific VLBI sessions (e.g., R1s, RDVs) and produce edited and ambiguity-resolved databases for use by the IVS. However, the Goddard VLBI group actually analyzes all VLBI sessions 'from scratch'. Beginning in 2000, the Goddard VLBI group began writing 'Analysis Comments' and making these available on the IVS session Web pages. These contain descriptions of how the data was analyzed and any issues that were found in the analysis, for example, clock breaks, missing data, or problems at the station. These are a valuable source of information for other scientists who use the data, and also provide a historical record of what was done and why. One issue is that since Goddard analyzes each database 'from scratch', the database that Goddard works with may not be the official IVS database. For example, USNO provides the official databases for the R4s and CRFs, BKG for the T2s and Euros. The editing and ambiguity resolution in the official database may be different than Goddard's database. Because of this there were sometimes slight inconsistencies in the Analysis Comments reports and the databases. Hence it is desirable that the institution that does the official analysis also write the Analysis Comments. USNO began submitting Analysis Comments beginning in 2015. Because of the time lag between when data is taken and when the sessions are analyzed, the first session that was done was R4665 (14DEC11XE). Going forward, I would like other IVS ACs that are responsible for submitting the IVS databases to submit Analysis Comments that will appear on the IVS session Web pages.

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Analysis Coordinator

IVS 2015+2016 Biennial Report

2 ITRF2014

In March 2013, Zuheir Altamimi issued a call to the geometric services (IDS, IGS, ILRS, IVS) for participation in ITRF2013. This was to include data through December 31, 2013, and the various techniques were supposed to submit their solutions in early 2014. Because of various control issues, the IGS had still not submitted a solution by December 2014. Zuheir asked the Analysis Coordinators of the different services if they would be willing to submit a solution including all available data through 2014, with a firm deadline of February 28, 2015. After internal discussions involving the IVS Combination Center and the IVS Analysis Centers the IVS agreed to this. Ten IVS Analysis Centers submitted solutions to the IVS Combination Center. The software and the number of ACs using it are, in order of popularity: A) Calc/Solve, five; B) VieVS, two; C) Geosat, one; D) Occam, one, and E) Quasar, one. The IVS Combination Center compared the input from the various ACs and produced a combined solution for use by the IERS Combination Centers (DGFI, IGN, and JPL). In the process of comparing the input from different ACs numerous issues were uncovered, most of which were subsequently fixed. Two of the submissions had such serious problems that they were not used in the IVS combination solution.

ITRF2014 differs from previous ITRFs in that it includes models for post-seismic deformation (PSD) at sites that had earthquakes. These models were derived by using data from GPS receivers located at these sites. Previously, PSD was handled on an ad hoc basis by different VLBI analysis packages. For example, Calc/Solve estimated splines for sites. Several IVS ACs compared the use of ITRF2014 vs. ITRF2008, and the general consensus was that ITRF2014 was a better a priori model.

In December 2016, the IERS Directing Board requested that the geometric services begin using ITRF2014 in their analysis as soon as possible. I passed this message along to the IVS ACs. In order to have a smooth transition I requested that ACs submit two sets of sinex files: one using ITRF2008 and the other ITRF2014 until a sufficient number of ACs had made the transition. GSFC began doing so in October 2016, and GFZ in January 2017. Several ACs indicated that they would switch over to ITRF2014 in the beginning of 2017.

3 Transition to Multitone Phasecal

In 2013, Arthur Niell (Haystack) suggested that the correlators should switch over to begin using Multi-tone phasecal. Prior to doing the switchover I thought it would be good to process some sessions using both multi-tone and single-tone phasecal and compare the results. Alessandra Bertarini (Bonn Correlator) agreed to correlate the CONT14 sessions using both methods. David Gordon (Goddard) edited these sessions, and I compared the results of the two data sets. The multi-tone results tended to be better by several criteria: The number of observations successfully correlated was larger. The session fit was slightly lower, indicating that the data within a session was more consistent. The baseline scatter over CONT14 was slightly less, indicating that the data were more consistent across sessions. However, it turned out that there was a difference of 1 cm in the up component of the station position for Zelenchukskaya between the single-tone and multi-tone. Ultimately this was traced to elevation dependence of the S-band phase-cal tones. The physical cause of this remains uncertain. These results were presented at the 2015 IVS Analysis Workshop held in Ponta Delgada, Portugal. During this workshop, suggestions were made for further investigations to try to isolate the cause, and further work was done over the next year, but the results were not conclusive. This issue was also discussed at a special meeting held at Haystack in September 2016. At the end of this meeting I decided to instruct the correlators to switch to multi-toned phase-cal for all sessions beginning after December 31, 2016. An email message was sent out to the ACs about this, with the caveat that people should be aware that there might be a change in the reference frame.

4 2015 Analysis Workshop in Ponta Delgada

The 2015 IVS Analysis Workshop was held in conjunction with the 2015 EVGA meeting in Ponta Delgada. In this section I will mention a few highlights.

Several groups (GSFC, BKG, and IAA) noticed systematic declination differences between the ICRF2 source positions (which used data into mid-2008), and solutions using data through 2014. GSFC, BKG, and IAA all see similar effects. The origin of this difference is still not understood, but appears to be related to having more data from southern stations, particularly AuScope and Warkworth. At the time of the meeting it was unclear which solution was better. Subsequently it looks like the solution with more data is more accurate. Some evidence for this is that this solution agrees better with X/Ka source positions from Chris Jacobs (JPL).

There was some discussion on how to handle galactic aberration. This is a real but small apparent change in the source position due to the acceleration of the Solar System around the galactic center. Subsequently an IVS Working Group on Galactic Aberration was established with Dan MacMillan (GSFC) as chair. They are to make a recommendation in early 2017.

It was proposed to increase the data rate for the R1s from 256 Mbs to 512 Mbs to improve the precision. This would also mean that twice as much data would need to be transferred. After some discussion it was decided to schedule one R1 a month at the increased data rate. Subsequently this has been increased to two R1s a month. An outstanding issue is to see if this actually improves the precision.

Thomas Hobiger (Onsala) suggested a software comparison project where different groups submitted their O-Cs for a ‘pseudo-session’. This would help ensure consistency of the packages. Several ACs participated in this effort. There were no major discrepancies uncovered.

5 2016 IVS Analysis Workshop

The 2016 Analysis Workshop was held in South Africa in conjunction with the 2016 IVS General Meeting.

Much of the discussion focused on differences between ITRF2008 and ITRF2014. Here is a summary of some of the findings. There is a 5 mm offset in Z between the two coordinate systems. There is also a shift in Ypole of about 0.05 mas. The post-seismic models agree very well with independent VLBI position time series. Using ITRF2014 there is better agreement between estimated polar motion and USNO finals. There is also better agreement with IGS. All of this indicates that ITRF2014 provides a better a priori position model than ITRF2008.

At the conclusion of the Analysis Workshop, I asked different software developers to share their plans for the future. In addition to Calc/Solve (GSFC) (one of the oldest and the most widely used VLBI analysis package) there were several new, and some not so new packages discussed. These include C++ (Chalmers), VieVs (Vienna), Vievs@GFZ (GFZ), Naviance (ESOC), ASCOT (BKG) and GINNS (NMA). It is good to have so many independent analysis systems. I am sure that friendly competition will be a spur for future improvement.

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Network Coordinator Report

Mario Bérubé, Rich Strand, Ed Himwich

Abstract This report includes an assessment of the network performance in terms of lost observing time for calendar years 2015 and 2016. Compared to previous years, the observing time loss has significantly increased, mainly due to broadband testing, long delays in repairs, and bad weather. Overall, the observing time loss was about 18% in 2015 and 21% in 2016. Despite higher statistics, the network performance was for the most part very good. The most significant identified cause of loss in 2015 was the scheduled broadband testing at Westford, which accounted for 91 station days being missed or 4% of total loss. The data loss of 2016 was dominated by maintenance and broadband testing accounting for 192 station days or 10% of total loss. RFI in S-band continues to be a significant source of data loss. A table of relative incidence of problems with various subsystems is presented. The report also presents analyses on station SEFDs and antenna slewing models using the 2015–2016 data set.

1 Network Performance

The network performance for the actual observing time is about the same as previous years. The apparent increase from previous years is due to our way of reporting statistics. We included stations that did not observe and were not included in correlation reports, resulting in an additional loss of 5% in 2015 and 10% in 2016. Broadband testing and antennas being down for repairs or maintenance accounted for most of this increase in data loss. RFI in S-band continues to be an important source of loss given that correlators dropped over 2.5% of recorded channels. Bad weather affected stations in many ways. Many hours were lost by antennas being stowed due to high winds or typhoons. Bad weather added unexpected delays to the maintenance of antennas and equipment. Some antennas were also damaged during storms. Antenna problems accounted for 9.3% of loss in 2016 due to long delays in delivering unique parts. Recording system problems were rare, and less than 1% of data were lost, mainly due to bad modules. Overall, operator performance was very good including reacting quickly to problems. Some problems due to operators happened, mainly at stations observing few geodetic experiments.

This network performance report is based on correlator and analysis reports from all 24-hour experiments correlated as of February 15, 2017. Experiments correlated at the VLBA were also included when data analysis reports provided relevant information on reasons for data loss. The 2015 data set is almost complete, because 227 of the 235 observed experiments, 97%, have been correlated. The average number of stations per experiment is 9.0 in 2015. The list of non-correlated experiments included four R&D, three CRDs, and one T2. The 2015 data set includes 1,288,881 dual frequency observations. About 75% of these observations were successfully correlated, and over 70% of them were used in the final IVS Analysis Reports. As of the date of submission of this report, only 166 of the 192 observed experiments, 86%, were correlated for 2016. The average number of stations per experiment is 10.7 in 2016. A total of 26 T2, R&D, OHG, CRDS, APSG, AOV, AUA, AUG, and HOB experiments were not correlated yet. The 2016 data set includes 1,046,001 dual

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IVS Network Coordinator

IVS 2015+2016 Biennial Report

frequency observations. About 76% of these observations were successfully correlated and over 70% of them were used in the final IVS Analysis Reports. Table 1 summarizes the data set used for the 2015–2016 network performance report. The data in parentheses represent the station days processed by the correlators. These values are used to compute loss in actual observing time.

Table 1 Data sets used for the 2015–2016 network performance report.

Year	Experiments	Station days	Obs	Correlated	Used
2015	227	2048 (1945)	1288881	75%	70%
2016	166	1775 (1593)	1046001	76%	70%

An important point to understand is that the network performance is expressed in terms of lost observing time. This is straightforward in cases where the loss occurred because operations were interrupted or missed. However, in other cases, it is more complicated to calculate. To handle this, a non-observing time loss is typically converted into an equivalent lost observing time by expressing it as an approximate equivalent number of recorded bits lost. As an example, a warm receiver will greatly reduce the sensitivity of a telescope. The resulting performance will be in some sense equivalent to the station having a cold receiver but observing for (typically) only one-third of the nominal time and therefore recording the equivalent of only one-third of the expected bits. In a similar fashion, poor pointing can be converted into an equivalent lost sensitivity and then equivalent fraction of lost bits. Poor recordings are simply expressed as the fraction of total recorded bits lost.

Using correlator reports, an attempt was made to determine how much observing time was lost at each station and why. This was not always straightforward to do. Sometimes the correlator notes do not indicate that a station had a particular problem, while the quality code summary indicates a significant loss. Reconstructing which station or stations had problems—and why—in these circumstances does not always yield accurate results. Another problem was that it is hard to determine how much RFI affected the data, unless one or more channels were removed and that eliminated the problem. It can also be difficult to distinguish between BBC and RFI problems. For individual station days, the results should probably not be assumed to be accurate at better than the 5% level.

The results here should not be viewed as an absolute evaluation of the quality of each station's performance. As mentioned above, the results themselves are only approximate. In addition, some problems such as weather and power failures are beyond the control of the station. Instead the results should be viewed in aggregate as an overall evaluation of what percentage of the observing time the network is collecting data successfully. Development of the overall result is organized around individual station performance, but the results for individual stations do not necessarily reflect the quality of operations at that station.

Because stations typically observe with more than one other station at a time, the average lost observing time per station is not equal to the overall average loss of VLBI data. Under some simplifying assumptions, the average loss of VLBI data is roughly twice the average loss of station observing time. This approximation is described in the Network Coordinator's section of the IVS 2001 Annual Report. The 2015–2016 results (Table 3) do not agree with this rough approximation. When reporting losses on single baseline, single frequency (S or X) observations, the correlators use stations included in the schedule file only.

The estimated ratios are affected by the high number of stations that were not included in the correlator reports for 2015 and 2016. For a better comparison with the previous year, corrected values are being used. The corrected statistics removed the non-correlated station days from the overall observing time. As shown in Table 2, using corrected statistics, the overall observing time loss is reduced to about 14% in 2015 and 12% in 2016. These corrected numbers are more in agreement with the 25%-24% non-correlated data. This corrected time loss shows the importance of quickly informing the IVS Coordinating Center when a station cannot participate in an experiment. In such a situation, a schedule is generated without the missing station. If these stations have been used to generate schedules, the successfully correlated data would have been less than 65% instead of the reported 75% and 76% for 2015 and 2016 respectively.

For 2015–2016, the actual percentage of dual frequency data that was not included by the analysts was approximately 30%. This is even larger (by approximately 5%) than the single baseline observations reported lost by the correlator. It is expected that this

Table 2 Major sources of losses for 2015–2016.

Year	Loss	Antenna	Miscellaneous	RFI
2015	18.2%	3.6%	4.7%	1.6%
2015 (corr)	13.8%	2.3%	1.3%	1.7%
2016	21.2%	9.2%	5.2%	2.3%
2016 (corr)	11.8%	3.2%	0.9%	2.5%

number should be higher both because of the dual frequency nature of the final observable and the fact that analysts use additional criteria beyond what is discussed here to decide when to exclude observations. However, it means in effect that only about 70% of the observations we attempted to collect were useful. This number is lower than previous years. This could be explained by baselines that were deselected because too many channels were dropped due to RFI. In addition, most of the WETTZELL-WETTZ13N observations were successfully correlated, but analysts rejected most of the data from that baseline. The rejection of this baseline accounted for about 5% of unused data for experiments that included these two stations at the same time.

Table 3 shows higher observing time loss for 2015–2016 when compared to previous years. As previously discussed, the 2015–2016 observing time loss was highly affected by broadband testing and by delays in repairing antennas or masers. Because these problems were known in advance, more than 103 station days in 2015 and 192 in 2016 were not included in schedules, thereby not affecting the correlation percentage. When removing these station days from the assessment, the corrected observing losses (Table 2) are comparable with previous years.

An assessment of each station's performance is not provided in this report. While individual station information was presented in some previous years, this practice seemed to be counter-productive. Although many caveats were provided to discourage people from assigning too much significance to the results, there was feedback that suggested that the results were being over-interpreted. Additionally, some stations reported that their funding could be placed in jeopardy if their performance appeared bad, even if it was for reasons beyond their control. Last and least, there seemed to be some interest in attempting to "game" the analysis methods to apparently improve individual station results. Consequently, only summary results

Table 3 Lost observing time. The percentage applies to a subset of the 1999–2000 experiments. Percentages for 2010 and 2011 are omitted but should be 10-20%.

Year	Percentage
1999-2000*	11.8
2001	11.6
2002	12.2
2003	14.4
2004	12.5
2005	14.4
2006	13.6
2007	11.4
2008	15.1
2009	21.5
2012	12.3
2013	16.2
2014	11.9
2015	18.2
2016	21.2

are presented here. Detailed results are presented to the IVS Directing Board. Each station can receive its own results by contacting the Network Coordinator (Ed.Himwich@nasa.gov).

For the purposes of this report, the stations were divided into two categories: **large N**: those that were included in 24 or more network experiments among those analyzed here and **small N**: those less than 24. The distinction between these two groups was made on the assumption that the results would be more meaningful for the stations with more experiments. Due to the high number of non-correlated station days, this analysis uses corrected statistics for 2015-2016 as shown in Table 4.

The average observing time loss from the large N group was much smaller than the average from the small N group, 12% versus 30% in 2015 and 10% versus 28% in 2016. The large N group accounts for more than 90% of the station days, so the large N group is dominant in determining the overall performance.

There are 23 and 22 stations in the large N group for 2015 and 2016 respectively. This is a significant increase from the 17 stations in this category in 2014. From the 2015 large N group, 11 stations observed in 49 or more experiments, and ten successfully collected data for approximately 92% or more of their expected observing time. The 2016 large N group had 12 stations that observed in 49 or more experiments, and nine collected 92% or more of their expected observing time.

Only one station from the 2015 large N group collected less than 70% of the scheduled data. No stations from the 2016 large N group collected less than 70% of the scheduled time. This is an improvement from previous years.

There are 23 and 21 stations in the small N group of 2015 and 2016 respectively. The range of lost observing time for stations in this category was 0%—100%. The median loss was approximately 25% in 2015 and 27% in 2016, a little worse than 2014 with 22%.

Table 4 Group analysis for 2015–2016. The average column shows the average lost observing time. The median column shows the median lost observing time. The 92% column shows the number of stations that observed in 49 or more experiments and successfully collected data for approximately 92% or more of their expected observing time.

	Large N				Small N		
Year	**Count**	**Average**	**Median**	**92%**	**Count**	**Average**	**Median**
2015	23	12.5%	11.7%	10	23	30.0%	24.9%
2016	22	10.8%	9.7%	9	21	27.7%	27.2%

The losses were also analyzed by sub-system for each station. Individual stations can contact the Network Coordinator (Ed.Himwich@nasa.gov) for the sub-system breakdown (and overall loss) for their station. A summary of the losses by sub-system (category) for the entire network is presented in Table 5. This table includes results since 2003 sorted by decreasing loss in 2016.

The categories in Table 5 are rather broad and require some explanation, which is given below.

Antenna This category includes all antenna problems, including mis-pointing, antenna control computer failures, non-operation due to wind through 2013, and mechanical breakdowns of the antenna. It also includes scheduled antenna maintenance. Wind stows were moved to Miscellaneous for 2014.

Clock This category includes situations in which correlation was impossible because the clock offset either was not provided or was wrong, leading to "no fringes". Maser problems and coherence problems that could be attributed to the Maser are also included in this category. For example, the phase instabilities reported for Kokee in previous year were included in this category. DBBC clock errors are included in this category.

Miscellaneous This category includes problems that do not fit into other categories, mostly problems beyond the control of the stations, such as power (only prior to 2012), (non-wind) weather through 2013, wind stows (moved here from the Antenna category starting in 2014), cables, scheduling conflicts at the stations, and errors in the observing schedule provided by the Operation Centers. For 2006 and 2007, this category also includes errors due to tape operations at the stations that were forced to use tape because either they did not have a disk recording system or they did not have enough media. All tape operations have since ceased. This category is dominated by weather and scheduling conflict issues. Westford VGOS testing, 28 station days, has been assigned to Miscellaneous for the year, 2014.

Operations This category includes all operational errors, such as DRUDG-ing the wrong schedule, starting late because of shift problems, operator (as opposed to equipment) problems changing recording media, and other problems.

Power This category includes data lost due to power failures at the sites. Prior to 2012, losses due to power failures were included in the Miscellaneous category.

Rack This category includes all failures that could be attributed to the rack (DAS), including the formatter and BBCs. There is some difficulty in distinguishing BBC and RFI problems in the correlator reports, so some losses are probably mis-assigned between the Rack category and the RFI category.

Receiver This category includes all problems related to the receiver, including outright failure, loss of sensitivity because the cryogenics failed, design problems that impact the sensitivity, LO failure, and loss of coherence that was due to LO problems. In addition, for lack of a more clearly accurate choice, loss of sensitivity due to upper X-band Tsys and roll-off problems are assigned to this category.

Recorder This category includes problems associated with data recording systems. Starting with 2006, no problems associated with tape operations are included in this category.

RFI This category includes all losses directly attributable to interference, including all cases of amplitude variations in individual channels, particularly at S-band. There is some difficulty

Table 5 Percentages of observing time lost by sub-system. Percentages for 2010 and 2011 were not calculated.

Sub-System	2016	2015	2014	2013	2012	2009	2008	2007	2006	2005	2004	2003
Antenna	43.4	20.0	14.8	39.6	18.1	29.4	19.2	34.6	19.0	24.4	32.9	17.8
Miscellaneous	24.3	25.8	35.1	9.4	6.9	15.3	12.8	7.6	18.0	8.0	8.0	6.0
RFI	10.7	8.6	13.2	6.4	11.8	5.9	14.8	10.4	11.6	6.2	5.0	9.3
Unknown	4.9	6.3	1.3	5.7	14.2	14.2	17.7	14.9	4.0	3.3	10.1	12.6
Rack	3.0	12.8	12.0	19.5	21.8	6.6	8.7	11.4	16.3	5.1	6.8	5.0
Receiver	2.8	10.1	13.9	7.7	11.7	18.6	13.8	14.9	20.8	24.2	18.0	25.2
Clock	2.5	0.9	0.2	3.5	1.8	1.9	0.5	0.3	4.9	14.5	0.5	3.4
Operations	2.3	5.9	4.1	2.5	2.0	1.2	2.3	0.0	2.0	4.7	6.1	3.6
Recorder	2.2	6.6	4.1	3.3	5.7	2.9	4.1	4.6	3.3	8.9	11.1	10.9
Power	1.9	1.2	0.4	2.1								
Shipping	1.6	1.3	0.0	0.9	3.6	4.0	5.4	1.0	0.0	0.2	1.4	6.1
Software	0.4	0.7	0.17	1.0	0.3	0.1	0.1	0.4	0.1	0.5	0.1	0.1

in distinguishing BBC and RFI problems in the correlator reports, so some losses are probably mis-assigned between the Rack category and the RFI category.

Shipping   This category includes all observing time lost because the media were lost in shipping or held up in customs or because problems with electronic transfer prevented the data from being correlated with the rest of the experiment's data.

Software   This category includes all instances of software problems causing observing time to be lost. This includes crashes of the Field System, crashes of the local station software, and errors in files generated by DRUDG.

Unknown   This category is a special category for cases where the correlator did not state the cause of the loss and it was not possible to determine the cause with a reasonable amount of effort.

Some detailed comments on the most significant issues for this year's data loss are given below.

- The two largest source of data loss for 2015-2016 are Antenna and Miscellaneous. The Antenna subsystem is mainly due to repairs at antennas that were delayed by months waiting for replacement parts. The high values of Miscellaneous are highly affected by broadband testing at a few stations and maser maintenance at Katherine and Yarragadee.
- RFI due to commercial systems continues to be an important factor of data loss, mostly in S-band. Hobart26, Sejong, Matera, and Zelenchukskaya are losing over 10% of their data to RFI. Fortaleza is still affected by RFI with an average loss of 8%.
- The proportion of losses attributed to Unknown, 4.9% in 2015 and 6.3% in 2016, have increased from 2014. Lack of communication (no logs, no emails) in some occasions made it difficult to categorize the loss.

Overall, while the network operated well for the most part, there are a few notable issues (in alphabetical order of station), for stations that lost more than 120 total observing hours regardless of the number of scheduled experiments for 2015–2016.

- Fortaleza had a significant cryogenic problem that was fixed in mid 2015 by replacing its compressor. Affected by RFI.
- Hart15m replaced an antenna motor gear box assembly damaged during a storm.
- Hobart12 broadband testing occurred in 2016. Multiple wind stows.
- Hobart26 was affected by RFI. Conflict with LBA. Antenna and rack failure.
- Katherine12 had DBBC and maser issues. Some wind stows.
- Kokee replaced an antenna azimuth bearing in 2016.
- Matera continued to have serious RFI.
- Medicina had required antenna maintenance and recorder issues as well as RFI.
- Ny-Ålesund had antenna azimuth gear box problems. Affected by bad weather.
- Sejong had serious RFI issues. Some non-detections due to equipment failure.
- Seshan had antenna maintenance.
- Svetloe had antenna maintenance and repairs.

- Urumqi had antenna maintenance and problems with media delivery.
- Warkworth had antenna elevation problems.
- Westford lost all scheduled experiments due to VGOS testing.
- Yarragadee had maser maintenance.

2 SEFD

When preparing schedules, it is important to have a good knowledge of the stations' SEFDs to compute the observation time for obtaining the expected SNR for each scan. These SEFD values were usually provided by stations to be included in the scheduling catalog.

After each experiment, the analysts compute effective SEFDs for each station using SNRANAL. The software, developed by John Gipson and maintained by Dan MacMillan, uses normalized SNR values determined at the time of correlation to compute S and X SEFDs for a specific experiment. Stations should look at the SNR summary file by using the specific link on every experiment Web page. These values are also published in the performance matrix page of each experiment. For example, the 2016 station performance for all stations can be found at https://lupus.gsfc.nasa.gov/sess/sesshtml/2016/station-perf16.html.

R1 and R4 SEFD results for 2015–2016 were used to compute average SEFDs for 30 stations. See Figure 1 for an example of results. The difficulty was to detect bad experiments that could bias the results. Data from stations observing with a warm receiver or having tracking problems were rejected from the analysis.

The computed SEFDs were compared with published values and flagged when differences were more than 20%. Of the 30 stations, eight stations have better SEFDs for X-band, and three for S-band, than published. On the other hand, 13 stations have higher SEFDs in X-band and nine in S-band.

For the moment, the software is mainly used as a tool to detect performance issues at stations, but two stations were updated to reflect the significant improvements in computed SEFD values. Further analyses are still needed, because many stations have large variations in SEFD values as shown in Figure 1.

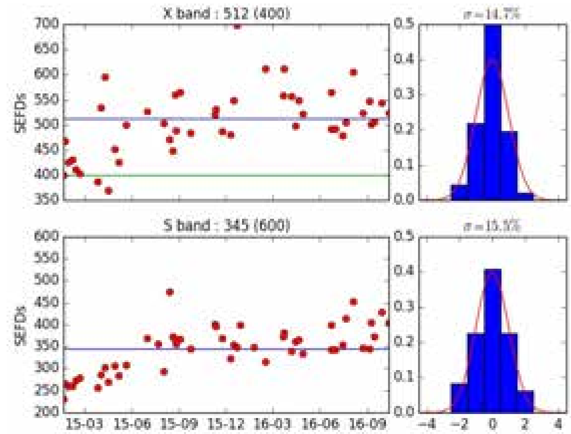


Fig. 1 SEFD example.

3 Antenna Slewing Models

Station log files are essential in analyzing station performance after each experiment. It was noticed that many stations had constant error messages showing they were still slewing at the beginning of PREOB or recording. Logs were showing that antennas could be late by more than 20 seconds in the normal operational mode.

The observing schedule uses a simple slewing model, a rate and offset for each axis, to determine when the antenna will arrive at the next source. If these models are wrong, the antenna does not arrive in time or waits longer than it needs to. Having precise slewing models is essential for optimum schedules. The rate represents the slewing speed in degrees per second of the antenna when at full speed. The offset is a constant value that includes the time to initiate the change of source, the time to reach maximum speed, and the time to slow down and lock on the source.

Some stations have turned on FLAGR in their FS so that antenna source acquisition information is available in their logs. Using this information, along with antenna and source positions, it is possible to estimate a slewing rate and an offset for azimuth and elevation.

Starting and arriving times were extracted from the 2015–2016 logs for 19 stations. The distances to travel in azimuth and elevation were generated by SKED. The new models were computed using a least square fit. The software to do this analysis for Azimuth/Elevation antennas was initially developed by the 2016 NVI interns — Lina Olandersson, Erik Thorsell, and Simon Strandberg. Mario Bérubé included statistical analysis to improve data selection.

See Figure 2 as an example of a computed versus a published slewing model for azimuth. In this case, the antenna is slower than expected by four deg/sec with a constant offset of nine seconds. The original model had no offset. Of the 19 stations analyzed, nine were moving slightly faster than scheduled. Stations with significant changes will be updated in the catalog in early 2017.

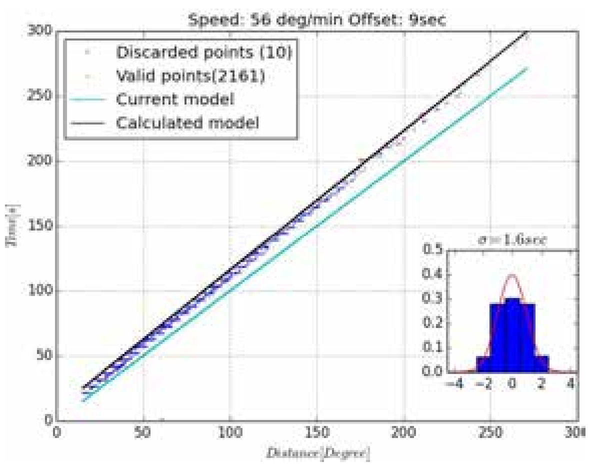


Fig. 2 Azimuth slewing model.

4 New Stations

There are prospects for new stations and antenna upgrades on several fronts. These include (in approximate order of how soon they will start regular observations):

- There are several antennas that started operational VGOS testing during the period of this report. These include: Ishioka (Japan), Kokee Park 12 m (USA), Wettzell South (Germany), and Yebes 13 m (Spain, part of RAEGE, see below).
- The three 12-m antennas that are part of the AuScope network (Australia) are being converted for VGOS use.
- In Sweden, the new twin 13-m telescopes at Onsala will start operational testing in the next year.
- In Norway, the new twin 13-m telescopes at Ny-Ålesund will start operational testing soon.
- In Spain/Portugal, the RAEGE (Atlantic Network of Geodynamical and Space Stations) project aims to establish a network of four fundamental geodetic stations, including radio telescopes that will fulfill the VGOS specifications: Yebes (1), Canary Islands (1), and Azores (2).
- In the USA, a new 12-m antenna was ordered for McDonald Geodetic Observatory (Texas) for VGOS observing.
- There is interest in India in building a network of four telescopes that would be useful for geodesy.
- Saudi Arabia is investigating having a combined geodetic observatory, which would presumably include a VLBI antenna.
- Colombia is investigating having a combined geodetic observatory, which would presumably include a VLBI antenna.
- An old ground station antenna in Peru is being converted for use in VLBI and may get some use for geodesy.
- Several old ground station antennas in Africa are being converted for use in VLBI as part of the African VLBI Network (AVN). It is not clear if these antennas will see any use for geodesy.

Many of these antennas will become available for use in the next few years. Efforts are being made to ensure that these antennas will be compatible with VGOS.

5 Network Coordination Activities

Network coordination during this period involved dealing with various network and data issues. These included:

- Reviewing all experiment “ops” messages, correlator reports, and analysis reports for problems and working with stations to resolve them.
- Responding to requests from stations for assistance.
- Identifying network station issues and working with the IVS Coordinating Center and the stations to resolve them. This year these included:
  - Encouraging timely delivery of log files, and
  - Validating DBBCs replacing existing systems.
- Participating in development of the new VEX2 schedule file standard.

- Providing catalog update information for station equipment and track lay-outs.
- Recognizing and reporting DBBC issues to station observing staff.
- Reviewing Mark 5 recording error checks for problems and informing correlator staff and station staff.
- Troubleshooting clock problems, including resolving the AuScope clock jump problem.
- Troubleshooting power supplies and identifying the correct parts for shipping.
- Troubleshooting video converters and organizing shipments to stations.
- Providing telescope pointing analysis and advice.
- Support, including software development, for the 12-m antennas at GSFC, KPGO, and the VGOS observing system operations.
- Support for TOW 2015.

6 Future Activities

Network coordination activities are expected to continue next year. The activities will largely be a continuation of the previous year's activities:

- Reviewing all experiment "ops" messages, correlator reports, and analysis reports for problems and working with stations to resolve them.
- Responding to requests from stations for assistance.
- Identifying Network Station issues and working with the IVS Coordinating Center and the stations to resolve them.
- Developing standard procedures for handling of station clocks for correlation.
- Updating Network Station configuration files.
- Organizing station registration with ITU.
- Improving Web presentation of IVS data and results.
- Providing support, including software development, for the 12-m antennas at GSFC, KPGO, MGO, and the VGOS observing system operations.
- Support for TOW 2017.
- Assisting with support for the CONT17 observing campaign.
- Other activities as needed.

IVS Technology Coordinator Report

Gino Tuccari [1,2]

Abstract These last years have seen intense activity aimed at setting up new VGOS stations, such as the beginning of VGOS observing in both experimental and operational fashion from more stations. An important activity has been dedication to verifying the broadband performance of the equipment in the entire processing chain, so as to practice this new observing mode. The signal chains in the field have different methods and approaches to producing the VGOS data, and harmonization has to be taken into account. This is not only useful but mandatory for the main elements to guarantee compatibility. Additionally those elements that can make the process well-integrated in a unique vision system should be taken under consideration. Advanced automatic or remote-controlled observing and correlation could involve a large amount of effort in the future; then we will need to dedicate careful evaluation and monitoring of the activities involving such tasks. In this short report I want to recall the main elements we need to focalize now and in the coming years.

1 Currently Available Processing Chains

In the IVS network a variety of different solutions are consolidated or under investigation. In the previous years, on multiple occasions, the definitions for a VGOS signal chain have been discussed in some detail (IVS VLBI2010 Workshop on Technical Specifications, Bad Kötzting, 2012 and different previous IVS reports in 2005 and 2009). Under these indications, developments have been proposed and experimentally evaluated by the different Technology Development Centers. As a result, there are a number of different solutions that need to be harmonized, also taking into consideration new possibilities and technology solutions which in the mean time have appeared.

There are some elements which can be mentioned as basic points. To summarize:

1. The actual frequency broadband, which is determined mainly by the local RFI. The 'official' 2.2–14 GHz VGOS band could actually present some restrictions or limitations to be actually covered as a site dependent element. In a VGOS network, any limitation at a site involves the entire network.
2. The number of antennas per station and their types in terms of the speed of their mechanical structures. A number of sites are planning or have available more than one VGOS antenna, which will offer a great level of flexibility. Antenna types and speeds are different, going from the slow legacy ones to the fastest, fully VGOS-compliant ones.
3. The feed type. Feed types having linear polarization output, even with direct generated circular polarization at the feed stage, are under investigation. A number of solutions are being studied to consider circular polarization reconstructed at the digital level at the station or at the correlator.
4. The LNA. LNA projects and commercial products are available from different sources with good performance. These components must be further considered from the point of view of RFI and for possible cryogenic filter inclusion.

1. INAF
2. Max Planck Institut für Radioastronomie

IVS Technology Coordinator

IVS 2015+2016 Biennial Report

5. The backend. Backend types at present developed by the IVS groups can be mainly distinguished as one of three types:

    - The broadband input within 2.2–14 GHz is flexibly tuned in pieces of 1 GHz afterwards sampled. Then a number of 32-MHz channels under 2-bit resampling are extracted at a maximum data rate of 16 Gbps, but the current common sustained data rate is 8 Gbps. The data representation can be either real or complex.
    - The input band is fully sampled in pieces of prefiltered 4-GHz chunks, then sampled and made available in digital format, from which narrow band channels (e.g., 64 or 32 MHz) can be extracted. A full data rate of 128 Gbps for the entire eight bands of 4 GHz is also possible.
    - The entire broadband is sampled with a sampling clock, to present aliased pieces of superimposed bands. The data are sampled with only three bits, which is a limitation in processing a potentially RFI-affected full wide band, and no narrow band channelization is available.

    Such different systems present different ancillary performances useful for phase, delay, and total power calibration.
6. Recording. For recording, we can distinguish again different types:

    - Mark 6, Octadisk2 types, which allow a maximum of 16 Gbps per unit, making use of removable disk packs that can be physically transferred from a station to a correlator and vice-versa.
    - Flexbuffer-like types, in different fashions developed or under development, which can permit even larger sustained recording data rates (up to 32 Gbps), with a fixed pool of internally connected disks. Data transfer to the correlators is then performed asynchronously with respect to observing.

    Both types of recorders permit the transfer of observed data in real time, when the network connections between the stations and the correlator permit.
7. Correlation. The correlation process is currently software-based and is performed with different software versions. The standard approach is to move the entire set of data from all the stations involved in an experiment to the correlator appointed for processing it.

2 VGOS Technology Evolution and Efforts

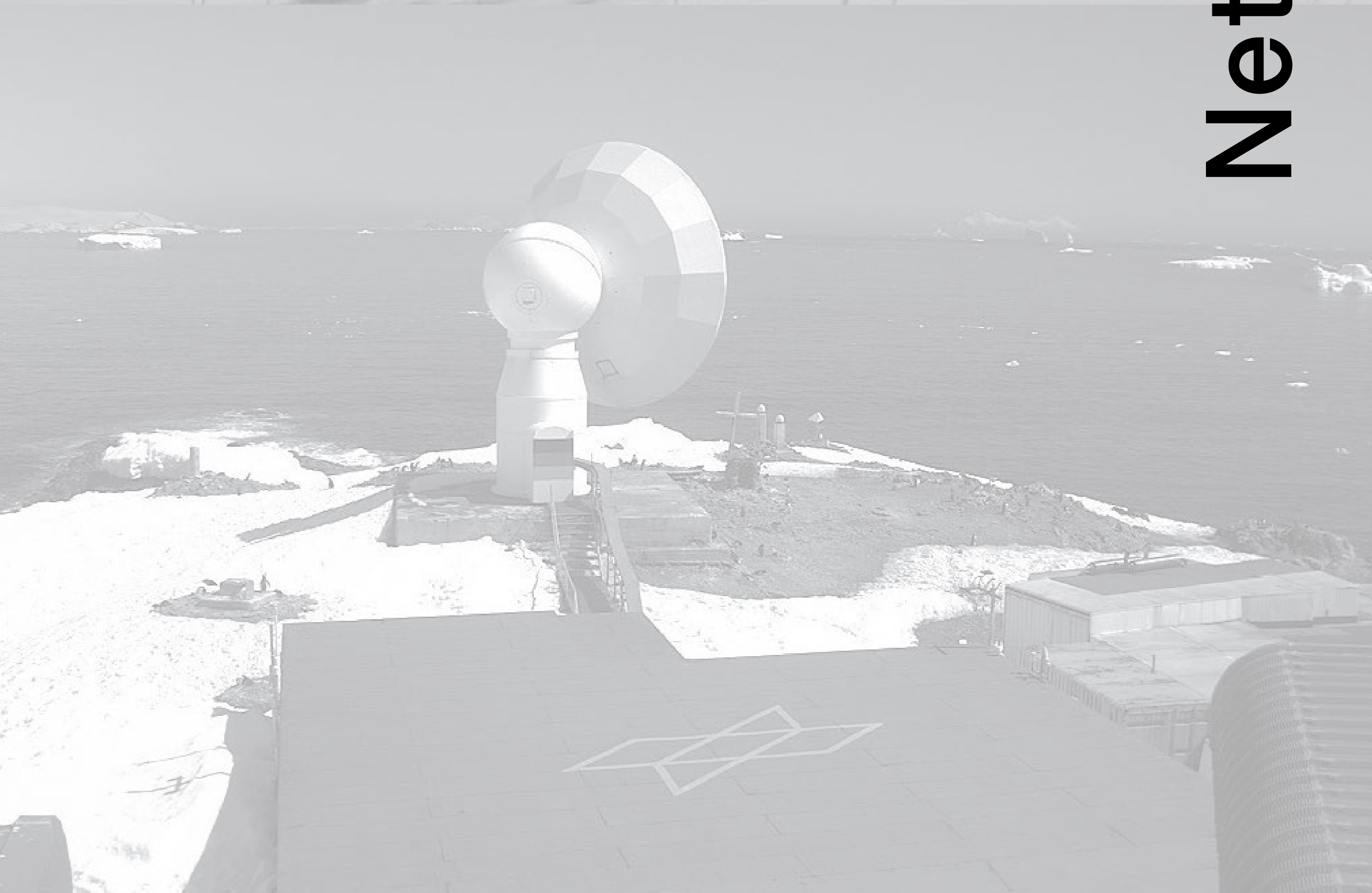
At present we can envisage directions from which an evolution could come, bringing benefits for VGOS networks. Here are the main ones that I would like to report.

1. Direct full VGOS band sampling
   This method, performed in multi-bit representation, could be a quantum leap in the signal chain. The entire data set represents, indeed, a huge opportunity to handle the output data, having elements driving the entire band information. Such elements will greatly simplify the signal chain and offer support for additional tasks, such as the full band polarization conversion in FPGA.
2. System interoperability
   As reported above, different systems, as developed and available at different stations, are a reality in the VGOS scenario. Compatibility between those systems is an element involving not only the individual systems in their structures, but also the capability of the entire system of accommodating different solutions offered to the community. A normalization process in this respect has to deal with such a capability, too.
3. Broadband coverage / RFI status
   The actual use of the entire band is problematic due to the presence of RFI, which varies at different sites. On the other hand, for compatibility with the legacy S/X stations, it would be important to observe the lower part of the band. An effort is then to be dedicated to the handling and mitigation of RFI, in opposition to the trend of simply cutting out this portion and moving the lower observation edge of the band to higher frequencies.
4. 24 hour/day, continuous observing sessions require a reduced contribution from the operators, so the efforts to introduce automatic and remotely-controlled observing sessions cover a fundamental aspect.
5. The data rate has to be increased to move the network to the planned goals. A first limitation looks to be the recording capability, with other different lim-

itations following immediately after, such as data storage capability, data transfer speed, and correlation capability. All of those elements need to be considered and addressed.

6. Distributed correlation is a necessity that can mitigate and optimize the massive amount of required data handling when more stations will be operative and the actual data rate will be increased. A studied approach, maybe supported by simulations, is required. Cloud computing could play a role. Additionally, more architectures need to be evaluated: similarly to the automatic station control, an automatic/remote correlation approach has to be evaluated for reducing the human contribution in a 'routine' VGOS network.

Network Stations



Moving from TIGO to AGGO

Argentinean-German Geodetic Observatory (AGGO) Report

Hayo Hase [1], Claudio Brunini [2], Augusto Cassino [3], Federico Salguero [3], José Vera [3], Alfredo Pasquaré [3]

Abstract The former Transportable Integrated Geodetic Observatory (TIGO) in Concepción, Chile, was moved to the vicinity of the town of La Plata, Argentina, constituting the new Argentinean-German Geodetic Observatory (AGGO). The period of 2015–2016 covers the move of eleven standard containers across the Andes mountain chain and setting up a new geodetic observatory near the La Plata river. Several overhaul measures were realized to begin operation with a refurbished instrumentation.

1 General Information

The successful VLBI operation of TIGO in Concepción came to an end in 2014 when the local partner, the Universidad de Concepción, was unable to continue its financial support of TIGO due to the losses and damages related to the M8.8 earthquake on February 27, 2010. However, the German government understood the need for a continued production of observing data obtained in the Southern hemisphere for the benefit of global geodesy. Consequently, the German administration was searching for a new project partner. In November 2013 a contract was signed between BKG and CONICET, Argentina.

1. Bundesamt für Kartographie und Geodäsie (BKG)
2. Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Fac. Cs. Astronómicas y Geofísicas Universidad Nacional de La Plata (UNLP)
3. Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET)

AGGO Network Station

IVS 2015+2016 Biennial Report

Since then a site near the capital town of the Province of Buenos Aires, La Plata, was investigated to become the home for a geodetic observatory. While in Chile the disassembling of TIGO progressed, the new platform had to be built in Argentina. The AGGO project was agreed to have three periods:

1. **[until the end of 2016]** termination of the construction of infrastructure and start of operation from the containers;
2. **[2017–2019]** transfer measuring and controlling equipment from containers to an operations building, while the operation for services is ongoing;
3. **[by 2020]** operation from operations building as a permanent observatory, abandoning the containers.

2 Activities during the Past Years 2015–2016

The year 2015 started with the last packings at the TIGO platform in Concepción. The documentation of the planned move was processed by Chilean authorities for exportation and by Argentinean authorities for importation. In parallel, two shipping companies had to provide trucks and air-suspended trailers for the move on land (as the age of the containers did not allow for a seaborne transport option). Finally, on April 11, 2015, the caravan consisting of eleven trucks and two accompanying cars left the town of Concepción in the early morning hours (Figure 1).

Nine days and about 3,600 km later, the final destination of AGGO was reached in the Pereyra Iraola Park at the urban limit of the town of La Plata, and the trucks were unloaded (Figure 2). At this time the foun-

Fig. 1 The caravan of eleven trucks while awaiting customs clearance at the *Paso Pino Hachado* border station in Argentina (April 11–13, 2015).

Fig. 3 The re-installation of the former TIGO radio telescope as AGGO radio telescope above a specially constructed platform was performed with the support of the company MT-Mecatronica from Chile (May 6, 2015).

dation for the containers and the radio telescope had already been prepared to set up the containers at their final position (Figure 3). However, there was still a lot of construction work to be done (operation building with kitchen, bathrooms, laboratories, electricity supply and Internet access). While the infrastructure work progressed step by step, the equipment and instruments had been unwrapped and reassembled also one after the other with new staff provided by CONICET.

Fig. 2 Downloading the 23-t container with the radio telescope inside at the AGGO platform (April 20, 2015).

The task is to set up AGGO as a fully functional fundamental station for geodesy, including:

Fig. 4 The geodetic reference marker of the radio telescope is part of the platform. The radio telescope is centered above the marker, which is conical and self-centers the radio telescope during the setup (May 6, 2015). The acronyms used for this radio telescope reference marker are listed in Table 1.

- 6-m offset radio telescope for VLBI observation within the IVS;
- 50-cm optical telescope with two-color 100-Hz laser system for SLR within the ILRS;
- GNSS stations supporting GPS, Glonass, and Galileo within the IGS, but also SIRGAS and the national geodetic reference frame POSGAR;
- time & frequency laboratory contributing to Universal Time as administrated by the Time Section of BIPM;

Table 1 Useful data about the VLBI reference point at AGGO (Figure 4).

Parameter	Value
DOMES No.	41596S002
CDP No.	7641 (axis intersection)
4-char code	AGGV
IVS 2-char id	Ag
approx. longitude	W 58.51398°
approx. latitude	S 34.8739°
approx. height	35.8 m

- super-conducting gravimeter for the ultra-precise observation of gravity variations within IGFS;
- local geodetic network for the local survey linking the local reference points;
- complementary sensors for meteorology, tilt, and seismicity;
- hydrological sensors in cooperation with GFZ Potsdam;
- data depository and local computer infrastructure;
- electricity supply robust against frequent power outages or instabilities;
- infrastructure for the well-being of staff working at AGGO.

On the occasion of the erection of the future operation building, the official inauguration of the AGGO project with the presence of the Argentinean Minister of Science, Technology and Innovation, Dr. Barañao, and the German Federal State Secretary, Mrs. Rogall-Grothe, took place on July 23, 2015 (Figure 5).

In order to make progress with this many-sided task, administrative support and special expertise were necessary. The supply with overhauled and new spare parts and materials for the installation from the Geodetic Observatory Wettzell was and is crucial. Supplies for AGGO coming from abroad require usually quite a long processing time for customs documents in order to enter into Argentina. This limits the speed of advance of the project.

In chronological order we received in situ help by:

- Hartmut Wziontek, Ilona Nowak (BKG) for the installation and operation of the superconducting gravity meter;
- Andreas Günthner, Stephan Schröder (GFZ) for the installation of hydrological sensors;
- Virginia Mackern, Laura Matteo (UNCuyo) with the local survey;

Fig. 5 The official inauguration of the AGGO project on July 23, 2015. Argentinean and German authorities cutting the inauguration tape of the operation building. From left to right: Prof. Dr. Brunini (AGGO), President Ing. Rodriguez (CIC), President Prof. Dr. Salvarezza (CONICET), Minister Dr. Barañao (MINCYT), State Secretary Mrs. Rogall-Grothe (BMI), President Prof. Dr. Kutterer (BKG), Ambassador Graf von Waldersee (AA).

- José Manuel Serna Puente (IGN, Spain) for the installation of the overhauled Dewar for the VLBI receiving system;
- Armin Böer (BKG) for the installation of the time&frequency laboratory;
- Ronald Guyot (T4Science, Switzerland) for modernizing and restarting the hydrogen masers.

3 Current Status

The status reached by end of the year 2016 is such that most of the construction work was completed and the instruments were set. Already in operation are:

- super-conducting gravity meter,
- hydrological sensors,
- frequency standards,
- GNSS receiver,
- part of the meteorological sensors.

Severe problems with the stability and continuity of the electric power supply and temporal floodings of the underground cabling system required adjustments in the construction and delayed rapid progress with the setup. The Internet access via optical fiber from/to the AGGO site is unfortunately also delayed, but should be done

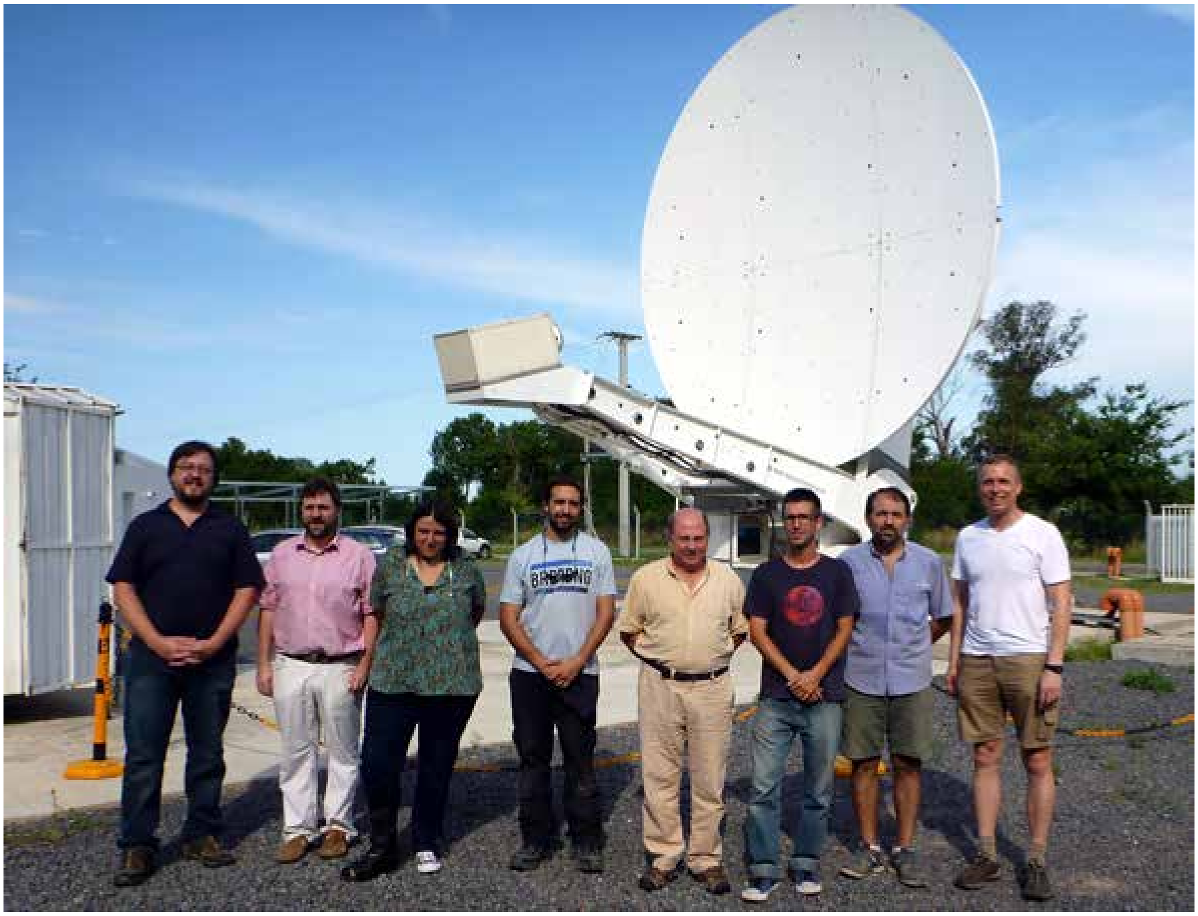


Fig. 6 AGGO staff in front of the 6-m offset radio telescope. From left to right: José Vera, Michael Häfner, Florencia Toledo, Augusto Cassino, Claudio Brunini, Federico Salguero, Alfredo Pasquaré, and Hayo Hase.

Table 2 AGGO staff in 2016.

Name	Background	Tasks	Email
Claudio Brunini	astronomer	scientific director	cbrunini@aggo-conicet.gob.ar
Hayo Hase	geodesist	head of operations	hayo.hase@bkg.bund.de
Augusto Cassino	electrical engineer	head of infrastructure and construction	acassino@aggo-conicet.gob.ar
Federico Salguero	electronic engineer	VLBI hardware	fsalguero@aggo-conicet.gob.ar
José Vera	electronic engnieer	VLBI software and system administrator	jvera@aggo-conicet.gob.ar
Alfredo Pasquaré	electronic engineer	time and frequency lab, GNSS	apasquare@aggo-conicet.gob.ar
Michael Häfner	physicist, engineer	SLR system	michael.haefner@bkg.bund.de
Florencia Toledo	optical engineer	SLR hardware	ftoledo@aggo-conicet.gob.ar
Romina Ronchi	administrator	administration	rronchi@aggo-conicet.gob.ar

during 2017. Consequently VLBI and SLR operations should resume in 2017.

The current staff situation is given in Table 2.

4 Future Plans

The plan for AGGO is to take part as an active network station for VLBI and SLR as well as for the other international services. This will require the training of staff in operations and the familiarization of operators with the instruments and equipment. Once some routine operations are established again, modernization projects will become more important.

Concerning future VLBI operation, a new VGOS radio telescope is considered to be important, and we have to see how we can manage this challenge.

Acknowledgements

The authors acknowledge the support of CONICET enabling the participation of Federico Salguero and José Vera at the IVS TOW 2015.

The AGGO team also expresses thanks for the received support from numerous individuals and institutions.

Badary Radio Astronomical Observatory 2015–2016 Report

Sergey Smolentsev, Valery Olifirov, Dmitry Ivanov

Abstract The current status as well as activities in 2015 and 2016 of the Badary Radio Astronomical Observatory are considered.

1 General Information

The "Quasar" VLBI Network is a unique Russian astronomical instrument created in the Institute of Applied Astronomy of the Russian Academy of Sciences (IAA RAS). The Network consists of three observatories including Svetloe in the Leningrad Region, Badary in Eastern Siberia, and Zelenchukskaya in the Northern Caucasus, and the Data Processing Center in St. Petersburg. Svetloe Observatory was the first to be put into operation in 1999, the next was Zelenchukskaya in 2002, and finally Badary in 2005 (Figure 1). Each observatory is equipped with at least three co-located instruments of different techniques: VLBI, SLR, combined GNSS receivers, and the DORIS system [1]. The main instrument in each of three observatories is a 32-m radio telescope (RT-32), which provides a completely automatic process of observing radio sources and satellites in a radiometric or a radio interferometric mode. The main technical characteristics of the antennas are presented in Table 1. The RT-32 radio telescopes equipped with highly sensitive receivers provide signal amplification in 1.35 cm, 3.5 cm, 6 cm, 13 cm, and from 18 cm to 21 cm frequency bands in both circular polarizations. The baselines of the radio interferometer vary from 2,000 to 4,400 km. All observatories are linked by optical fiber lines and are equipped with identical hydrogen Time Standards, Water Vapor Radiometers, and meteorological stations, which are used by all types of observations.

Institute of Applied Astronomy of RAS

Badary Network Station

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Fig. 1 Badary Observatory.

2 Activities during the Past Two Years

Upgrading of the "Quasar" VLBI Network started in 2012. The aim of the upgrade was to create a Radio Interferometer of the new generation for improving the accuracy, reliability, and efficiency of providing the Earth rotation parameters to consumers in Russia and abroad. The Radio Interferometer of the new generation is designed to operate as part of the "Quasar" and international VLBI Networks. Currently, this new Radio Interferometer operates successfully and consists of two multi-band fast rotating Antenna Systems with

Table 1 Specifications of RT-32.

Mount	alt-azimuth
Configuration	Cassegrain
Subreflector scheme	asymmetrical
Main mirror diameter	32 m
Subreflector diameter	4 m
Focal length	11.4 m
Azimuth speed	1.0°/sec
Elevation speed	0.5°/sec
Limits by Az	±265°
Limits by El	0° – 85°
Axis offset	0.9 ± 1.0 mm
Tracking accuracy	±10 arcsec
Surface accuracy (RMS)	0.5 mm
Frequency range	1.4 – 22 GHz
Polarization	LCP + RCP

a mirror diameter of 13.2-m (RT-13), which were installed at the Zelenchukskaya and Badary (Figure 2) observatories in 2015 [2]. Table 2 presents some specifications of the RT-13 Antenna System, which meet all requirements of the VGOS program.

Fig. 2 The RT-13 Antenna at the Badary observatory.

During 2015—2016 RT-32 and the RT-13 radio telescopes at the Badary observatory participated in both IVS and domestic (Ru-E, Ru-I, and R) VLBI observations. Activities of the observatory are presented in Table 3 and Table 4. e-VLBI data transfer is used at Badary for the domestic sessions. Since 2015, the RT-13 radio telescope participates in the following geodetic sessions:

Table 2 Specifications of the RT-13.

Mount	alt-azimuth
Configuration	Cassegrain
Subreflector scheme	ringfocus
Main mirror diameter	13.2 m
Subreflector diameter	1.48 m
Focal length	3.7 m
Azimuth speed	12.0°/sec
Elevation speed	6.0°/sec
Limits by Az	±245°
Limits by El	6° – 109°
Axis offset	-0.3 ± 0.5 mm
Operation	24 h/7 d
Tracking accuracy	±15 arcsec
Surface accuracy (RMS)	0.3 – 0.1 mm
Frequency range	2–40 GHz
The surface efficiency	> 0.7
Polarization	LCP + RCP

- The 0.5–one-hour geodetic program in S/X bands for UT1 determination (“R”, on the baseline ZELRT13V–BADRT13V).
- The test geodetic program in X/Ka and S/X/Ka bands (“Ru-TEST”, on the baseline ZELRT13V–BADRT13V).
- The 23-hour geodetic program in S/X bands for improving the position data of the RT-13 antennas (“Ru-TEST”, all “Quasar” antennas).
- Miscellaneous test sessions, including international cooperation (“Ru-TEST”).

Table 3 VLBI observations of RT-32 at Badary Observatory.

Sessions	2015	2016
IVS-R4	25	19
IVS-T2	2	5
EUROPE	2	5
R&D	4	4
Ru-E	37	35
Ru-I	356	370

Table 4 VLBI observations of the RT-13 of Badary Observatory.

Sessions	2015	2016
R	137	1378

3 Future Plans

In the next two years, the Badary Observatory will continue to participate in IVS and domestic VLBI observations, upgrade the existing equipment, and replace the obsolete equipment.

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Effelsberg Radio Observatory 2015–2016 Biennial Report

Uwe Bach, Alex Kraus

Abstract The 100-m radio telescope of the Max-Planck-Institut für Radioastronomie (MPIfR) is one of the largest fully steerable single-dish radio telescopes in the world and a unique high-frequency radio telescope in Europe. The telescope can be used to observe radio emissions from celestial objects in a wavelength range from 90 cm (300 MHz) down to 3.5 mm (90 GHz).

1 General Information

The Effelsberg radio telescope was inaugurated in 1971 and was (for almost 30 years) the largest fully steerable single-dish radio telescope in the world. It is situated in a protected valley near Bad Münstereifel (about 40 km southwest of Bonn) and operated by the Max-Planck-Institut für Radioastronomie (MPIfR) on behalf of the Max-Planck-Society (MPG). To this day, it is the largest radio telescope in Europe and is mostly used for astronomical observations.

This extremely versatile and flexible instrument can be used to observe radio emissions from celestial objects in a wavelength range from about 1 m (corresponding to a frequency of 300 MHz) down to 3.5 mm (90 GHz). The combination of the high surface accuracy of the reflector (the mean deviation from the ideal parabolic form is ∼0.5 mm rms) and the construction principle of ‘homologous distortion’ (i.e., the reflector in any tilted position has a parabolic shape with a well-defined, but shifted, focal point) enables very sensitive observations to be made at high frequencies (i.e., $\nu > 10$ GHz).

The wide variety of observations with the 100-m radio telescope is made possible by the good angular resolution, the high sensitivity, and a large number of receivers which are located either in the primary or in the secondary focus. Together with a number of distinct backends dedicated to different observing modes, this provides excellent observing conditions for spectroscopic observations (atomic and molecular transitions in a wide frequency range), high time-resolution (pulsar observations), mapping of extended areas of the sky, and participation in a number of interferometric networks (e.g., IVS, mm-VLBI, EVN, and Global VLBI etc.).

Table 1 Effelsberg telescope properties.

Name	Effelsberg
Coordinates	6:53:01.0 E,+50:31:29.4 N
Mount	azimuthal
Telescope type	Gregorian (receivers in primary and secondary focus)
Diameter of main reflector	100 m
Focal length of prime focus	30 m
Focal length of secondary focus	387.7 m
Surface accuracy	0.55 mm rms
Slew rates	Azi: 25 deg/min, Elv: 16 deg/min
Receivers for Geodetic observations	3.6 cm/13 cm secondary-focus (coaxial)
T_{sys} (3.6 cm/13 cm)	25 K, 200 K
Sensitivity (3.6 cm/13 cm)	1.4 K/Jy, 0.5 K/Jy
HPBW (3.6 cm/13 cm)	81 arcsec, 350 arcsec
Tracking accuracy	∼ 2 arcsec

Max-Planck-Institut für Radioastronomie, Bonn, Germany

Effelsberg Network Station

IVS 2015+2016 Biennial Report

Fig. 1 Aerial image of the Effelsberg radio observatory. Shown are the 100-m Effelsberg antenna and the institute's building (left of the antenna). Effelsberg hosts also a station of the European Low Frequency Array (LOFAR), seen in the lower part of the picture.

2 Staff

The staff at Effelsberg consists of about 40 people, including telescope operators; technical personnel for receivers, electronics, and mechanics; scientists, and administrative personnel. Involved in IVS activities are, beside the telescope operators, **Dr. Alexander Kraus** as station manager and scheduler for the 100-m Effelsberg telescope and **Dr. Uwe Bach** as support scientist and VLBI friend. **Thomas Georgi**, who was involved in schedule and disk management and shipping for several years, retired in January 2017. His duties will be taken over by two of the telescope operators, **Markus Keseberg** and **Peter Vogt**.

3 Activities during the Past Years

Effelsberg has participated regularly in the EUROPE IVS sessions since 1991. In 2015 and 2016, the experiments EUR135, EUR138, EUR142, and EUR144 were observed. About 30% of the observing time of the Effelsberg antenna is used for VLBI observations. Most of them are astronomical observations for the European VLBI Network (EVN), High Sensitivity Array (HSA), Global MM VLBI Array (GMVA), or other global networks, but also geodetic VLBI observations within the IVS are performed. Since 2011, the Russian Astro Space Center has been operating a 10-m space radio antenna on board the satellite SPEKTR-R (RadioAstron) to perform VLBI observations. Effelsberg is highly involved in the ground based support of this mission, and 296 of a total of 428 VLBI observations in 2015 and 208 of 368 observations in 2016 were connected to RadioAstron observations.

Two Mark 6 recorders have been installed for data acquisition of the DBBC2. The two recorders are equipped with large 32 TB or 64 TB diskpacks that stay in Effelsberg, providing a total local storage capacity of 256 TB. All recorded data is e-transferred via the e-VLBI network to the correlators in Bonn, at the ASC in Moscow, and at JIVE. For storage of

Effelsberg EVN data at JIVE, the MPIfR provided a 120 TB raid system for JIVE as well.

The K-band receiver (18 to 26 GHz) that was installed in the secondary focus in 2014 (see Figure 2) has been commissioned and is in regular use for VLBI observations of the EVN, HSA, and RadioAstron.

In 2015 a new broadband receiver for C- and X-band, covering a frequency range of 4 GHz to 9.3 GHz (7.5 cm to 3.2 cm), was installed in the secondary focus cabin (top left in Figure 2). Primarily, the receiver has been built for high sensitivity continuum observations and spectroscopy of molecule transitions, such as Formaldehyde and Methanol. With its two linear polarizations it is not naturally the first choice for VLBI observations, as most stations in VLBI record left and right-circular polarization (LCP and RCP) signals.

In December 2016, the regular real time e-VLBI observations were scheduled at 6.65 GHz, but the standard VLBI 6-GHz prime focus receiver box at Effelsberg was not available due to maintenance. To support the observations it was decided to use the new C+ receiver. The correlation and calibration of the recorded data was successful, and Effelsberg showed good and stable fringes from the start of the experiment. Further tests to convert the linear to circular polarization using a newly developed algorithm (Marti-Vidal et al. 2016, A&A, 587, p. 143) are in progress. Depending on the results, the new receiver might be an option for C-band observations in general.

4 Current Status

Effelsberg uses the DBBC2, Fila10G, and a Mark 6 recorder for all EVN, global, RadioAstron, and geodetic VLBI observations. Most of the recorded data is e-transferred to the correlators in Bonn, at the ASC in Moscow, and at JIVE. In addition there are two NRAO RDBEs and a Mark 5C recorder that are used for observations with the VLBA, HSA, and GMVA. Mark 5 diskpacks to Socorro are still being shipped. Both VLBI backends and their recorders are controlled by the Field System (current release FS-9.11.8). The observatory is connected via a 10 GE optical fiber to the e-VLBI network and can do real time e-VLBI observations (performed about monthly within the EVN) and e-transfers.

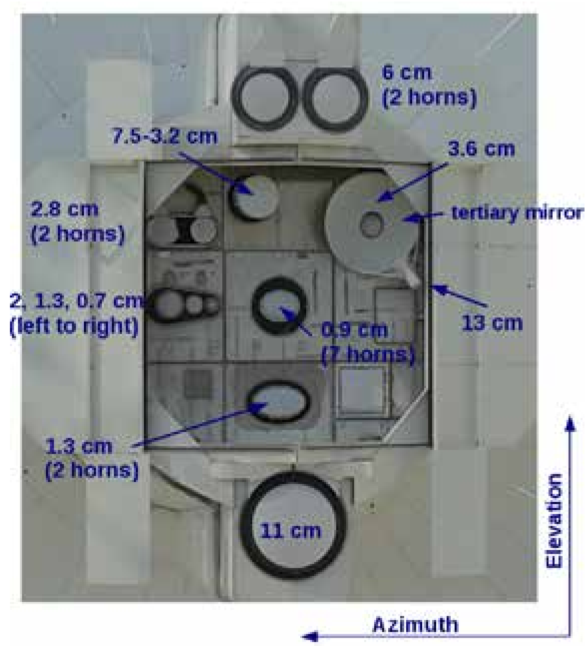

Fig. 2 Picture of the secondary focus cabin with several astronomical receivers, e.g. the new K-band with two horns, the new C/X-band, and the geodetic S/X system with the 3.6-cm horn and the tertiary mirror for the 13-cm horn.

5 Future Plans

Upgrades for several receiving systems are planned for 2017. The construction of a new Q-band receiver (38 to 50 GHz) was delayed because of unexpected problems in the RF chain but is planned to be installed in summer 2017. In parallel the installation of a Ku-band receiver (12 to 18 GHz) is planned as well. The new receivers will provide wideband IF signals of 2.5 GHz and 4 GHz bandwidth which can be used with the next generation of digital VLBI backends and recorders (e.g., DBBC3 and Mark 6) to record data at recording rates of up to 32 Gbps. The installation of a DBBC3 is planned for summer 2017.

Fortaleza Station Report for 2015 and 2016

Pierre Kaufmann [1], A. Macilio Pereira de Lucena [2], Adeildo Sombra da Silva [1]

Abstract This is a brief report about the activities carried out at the Fortaleza geodetic VLBI station (ROEN: Rádio Observatório Espacial do Nordeste), located in Eusébio, CE, Brazil, during the period from January 2015 until December 2016. The total observed experiments consisted of 183 VLBI sessions and continuous GPS monitoring recordings. About 92% of VLBI recorded data was transmitted through high speed network.

1 General Information

The Rádio Observatório Espacial do Nordeste, ROEN, located at INPE facilities in Eusébio, nearly 30 km east of Fortaleza, Ceará State, Brazil, began operations in 1993. Geodetic VLBI and GPS observations are carried out regularly, as contributions to international programs and networks. ROEN is part of the Brazilian space geodesy program, which was initially conducted by CRAAE (a consortium of the Brazilian institutions Mackenzie, INPE, USP, and UNICAMP) in the early 1990s. The program began with antenna and instrumental facilities erected, with activities sponsored by the U.S. agency NOAA and the Brazilian Ministry of Science and Technology's FINEP agency.

ROEN is currently coordinated by CRAAM, Center of Radio Astronomy and Astrophysics, Engineering School, Mackenzie Presbyterian University, São Paulo, in agreement with the National Institute for Space Research INPE. The activities are currently carried out under an Agreement of Cooperation which was signed between NASA—representing research interests of NOAA and USNO—and the Brazilian Space Agency, AEB, and which was extended until 2021. Under the auspices of the NASA-AEB Agreement, a contract was signed between NASA and CRAAM, Mackenzie Presbyterian Institute and University to partially support the activities at ROEN. In 2014, the contract was renewed for five more years.

The counterpart of the operational costs, staff, and support of infrastructure are provided by INPE and by Mackenzie.

2 Main Instruments

The largest instrument at ROEN is the 14.2-m radio telescope on an alt-azimuth positioner. It is operated at S- and X-bands, using cryogenic radiometers. The system is controlled by the Field System, Version 9.11.6. Observations are recorded with a Mark 5A system and transmitted through a high speed network either to the U.S. (WACO and Haystack correlators) or to the Bonn correlator in Germany at rates of about 220 Mbps. The 1 Gbps link was accomplished in 2007. It integrates and is sponsored by the Brazilian Research Network—RNP. One Sigma-Tau hydrogen maser clock standard is operated at ROEN. GPS monitoring is performed within a cooperative program with NOAA (USA). There is a Leica System 1200 installed at the station that operates continuously. The collected data are provided to the NOAA/IGS center and to the Brazilian IBGE center. ROEN has

1. Universidade Presbiteriana Mackenzie, CRAAM and INPE, Rádio Observatório Espacial do Nordeste, ROEN
2. Instituto Nacional de Pesquisas Espaciais, INPE

Fortaleza Network Station

IVS 2015+2016 Biennial Report

Fig. 1 14.2-m radio telescope.

all basic infrastructures for mechanical, electrical, and electronic maintenance of the facilities.

3 Staff

The Brazilian space geodesy program is coordinated by one of the authors (PK), who is Brazil's AEB representative in the NASA-AEB Agreement. The coordination receives support from the São Paulo office at CRAAM/Instituto and Universidade Presbiteriana Mackenzie, with administrative support from Valdomiro M. S. Pereira and Lucíola Russi. The Fortaleza Station facilities and geodetic VLBI and GPS operations are managed on site by Dr. Antonio Macilio Pereira de Lucena (INPE), assisted by Eng. Adeildo Sombra da Silva (Mackenzie), and the technicians Emerson Costa (Mackenzie) and Francisco Renato Holanda de Abreu (Mackenzie).

4 Current Status and Activities

4.1 VLBI Observations

In the years 2015 and 2016, Fortaleza participated of geodetic VLBI sessions described in Table 1.

Table 1 2015 and 2016 session participation.

Session Type	Number of Sessions
IVS-R1	73
IVS-R4	74
IVS-T2	9
R&D	14
CRF	6
OHIG	7

4.2 Operational and Maintenance Activities

The summary of activities performed in the period is listed below:

1. Repair and maintenance of the following equipments: cryogenic system, Mark IV acquisition system, Mark 5A recorder, antenna mechanical and electrical systems, angle encoders system, and receiver telemetry.
2. Replacement of one Sigma-Tau maser power supply unit.
3. Restoration and painting of the antenna.
4. Repair of electrical motors and gear boxes of antenna drives.
5. Renewal of electrical structure of main building.
6. Repair of the angle transducer spare unit.
7. Operation and maintenance of geodetic GPS (NOAA within the scope of NASA contract).
8. Operation and maintenance of power supply equipment at the observatory (main and diesel driven standby).
9. Transferring of recorded data through high speed network.

4.3 GPS Operations

The IGS network GPS receiver operated regularly at all times during 2015 and 2016. Data were collected and uploaded to IGS/NOAA.

Goddard Geophysical and Astronomical Observatory

Heidi Riesgo, Katherine Pazamickas

Abstract This report summarizes the technical parameters of the Very Long Baseline Interferometry (VLBI) systems at the Goddard Geophysical and Astronomical Observatory (GGAO) and provides an overview of the activities that occurred in 2015–2016 as well as the outlook lists the outstanding tasks to improve the performance.

1 Location

The Goddard Geophysical and Astronomical Observatory (GGAO) consists of a 5-meter radio telescope for VLBI, a new 12-meter radio telescope for VGOS development, a 1-meter reference antenna for microwave holography development, an SLR site that includes MOBLAS-7, the NGSLR development system, a 48″ telescope for developmental two-color Satellite Laser Ranging, a GPS timing and development lab, a DORIS system, meteorological sensors, and a hydrogen maser. In addition, we are a fiducial IGS site with several IGS/IGSX receivers.

GGAO is located on the east coast of the United States in Maryland. It is approximately 15 miles NNE of Washington, D.C. in Greenbelt, Maryland.

NASA GSFC

GGAO Network Station

IVS 2015+2016 Biennial Report

Table 1 Location and addresses of GGAO at Goddard.

Longitude	76.4935° W
Latitude	39.0118° N
MV3 Code 299.0 Goddard Space Flight Center (GSFC) Greenbelt, Maryland 20771	
http://cddis.nasa.gov/ggao/vlbi.html	

2 Technical Parameters

The 5-m radio telescope for VLBI at MV3 was originally built as a transportable station; however, it was moved to GGAO in 1991 and has been used as a fixed station. In the winter of 2002, the antenna was taken off its trailer and permanently installed at GGAO. This antenna has not been operable for the past two years and it is not operable at this present time.

In October 2010, construction of the new 12-meter VGOS developmental antenna was completed. This antenna features all-electric drives and a Cassegrain feed system. Integration of the broadband receiver and the associated sub-systems is underway as a joint effort between Harris Corporation and the MIT Haystack Observatory.

The technical parameters of the radio telescopes are summarized in Table 2.

3 Staff of the VLBI Facility at GGAO

GGAO is a NASA research and development and data collection facility. It is operated under the Space Communication Network Services (SCNS) contract by Har-

Table 2 Technical parameters of the radio telescopes at GGAO.

Parameter	5-m	12-m
Owner and operating agency	NASA	NASA
Year of construction	1982	2010
Diameter of main reflector d	5 m	12 m
Azimuth range	$\pm 270°$	$\pm 270°$
Azimuth velocity	$3°/s$	max. $5°/s$
Azimuth acceleration	$1°/s^2$	$1.3°/s^2$
Elevation range	$\pm 90°$	$5 - 88°$
Elevation velocity	$3°/s$	max. $1.5°/s$ (elevations $> 70°$)
Elevation acceleration	$1°/s^2$	$1.3°/s^2$
Receiver System		
Focus	Cassegrain	Cassegrain
Receive Frequency	2–14 GHz	2–14 GHz
T_{sys}	100 K	50 K (Theoretical)
Bandwidth	512 MHz, four bands	512 MHz, four bands
G/T	26 dB/K	43 dB/K
VLBI terminal type	CDP	VGOS
Recording media	Mark IV	Mark 6

ris Corporation. The staff at GGAO consists mainly of two operators and one backup engineer. The Harris staff includes Katherine Pazamickas and Jay Redmond conducting VLBI operations and maintenance at GGAO with the support of Heidi Riesgo.

4 Mission Support

Having ceased VLBI operations in May 2007, MV3 continues on a full time basis to be a major component in the program to demonstrate the feasibility of the VGOS broadband delay concept. Working under the guidance of the Harris team, the VGOS antenna has participated in many VLBI Global Observing System (VGOS) 24-hour experiments.

5 Recent Activities

Much of the 2015 and 2016 activities at GGAO have been focused on experiments using the VGOS 12-m antenna. However, there were some other activities worth noting:

- The digital backend software was upgraded.
- IVS observations were conducted using the Mark 6 recorders to demonstrate the VGOS capabilities on a regular twice a month schedule.
- RDBEs, Mark 6, UDC and Field System computer software were integrated.
- Additional testing of the 16 Gbps VLBI recording, demonstrated using Mark 6 was performed.
- Tried to understand the azimuth wrap and how and why it damages cables, along with taking cable delay measurements to use along with the observation data.

6 Outlook

GGAO will continue to support VGOS, e-VLBI, and other developmental observations and activities during the upcoming two years. Tentative plans for 2017 include:

- Repairing azimuth and elevation gearboxes seal to prevent oil contamination.
- Conducting IVS observations using the Mark 6 recorders to demonstrate the VGOS capabilities on a regular twice a month schedule.
- Continuing to investigate how and why the cables are degrading at the azimuth wrap.
- Continuing taking cable delay measurements for observation data correlation.

- Trying to understand why the antenna will not move in elevation under computer control when first started up on cold mornings.
- Participating in the VGOS part of the Continuous VLBI Campaign 2017 (CONT17).
- Developing MCI monitoring system display.

Hartebeesthoek Radio Astronomy Observatory (HartRAO)

Marisa Nickola, Roelf Botha, Ludwig Combrinck, Aletha de Witt, Jacques Grobler, Philip Mey, Jonathan Quick, Pieter Stronkhorst

Abstract HartRAO is the only fiducial geodetic site on the African continent, and it participates in global networks for VLBI, GNSS, SLR, and DORIS. This report provides an overview of geodetic VLBI activities at HartRAO during 2015 and 2016, including progress with the VGOS project.

1 Geodetic VLBI at HartRAO

Hartebeesthoek is located 65 km northwest of Johannesburg, just inside the provincial boundary of Gauteng, South Africa. HartRAO is located 32 km away from the nearest town, Krugersdorp. The telescopes are situated in an isolated valley which affords protection from terrestrial radio frequency interference. HartRAO currently operates both a 15-m and a 26-m radio telescope. A new 13.2-m VGOS radio telescope is under construction. The 26-m is an equatorially mounted Cassegrain radio telescope built by Blaw Knox in 1961. The telescope was part of the NASA deep space tracking network until 1974 when the facility was converted to an astronomical observatory. The 15-m is an az-el radio telescope built as a Square Kilometre Array (SKA) prototype during 2007 and converted to an operational geodetic VLBI antenna during 2012. The telescopes are co-located with an ILRS SLR station (MOBLAS-6), a new Russian satellite laser and radio ranging system ≪Sazhen-TM+OWS≫ (not fully operational yet), an IGS GNSS station (HRAO), a seismic vault, and an IDS DORIS station (HBMB) at the adjoining South African National Space Agency Earth Observation (SANSA EO) site. HartRAO is also a full member of the EVN.

HartRAO

HartRAO Network Station

IVS 2015+2016 Biennial Report

Fig. 1 New additions at fundamental site HartRAO: VGOS installation bottom left with, to its right, the ≪Sazhen-TM+OWS≫ (GNSS one-way station, Sazhen-TM quantum-optical station and control room).

2 Technical Parameters of the 15-m and 26-m Telescopes at HartRAO

Table 1 contains the technical parameters of the HartRAO 15-m and 26-m radio telescopes, while Table 2 and Table 3 contain technical parameters of the HartRAO 15-m and 26-m receivers, respectively. The current data acquisition systems consist of a DBBC terminal and a Mark 5B+ recorder for both the 15-m and the 26-m antennas. A Mark 5C recorder is used for e-transfer of data and conditioning and testing of disk packs. A 102-TB Flexbuf reading system is also available for astronomical VLBI use. Three hydrogen masers are available—the EFOS-28, which is currently employed for VLBI on the 15-m antenna, the iMaser 72, currently employed on the 26-m antenna, and the resuscitated EFOS-6.

Table 1 Antenna parameters.

Parameter	Hart15M	HartRAO
Owner and operating agency	HartRAO	HartRAO
Year of construction	2007	1961
Radio telescope mount	Offset az-el	Offset equatorial
Receiving feed	Prime focus	Cassegrain
Diameter of main reflector d	15 m	25.914 m
Focal length f	7.5 m	10.886 m
Focal ratio f/d	0.5	0.42
Surface error of reflector (RMS)	1.6 mm	0.5 mm
Short wavelength limit	3 cm	1.3 cm
Pointing resolution	0.001°	0.001°
Pointing repeatability	0.004°	0.004°
Slew rate on each axis	Az: 2° s^{-1} El: 1° s^{-1}	HA: 0.5° s^{-1} Dec: 0.5° s^{-1}

Table 2 Parameters of the 15-m co-axial receiver.

Parameter	X-band	S-band
Feeds	stepped horn	wide-angle corrugated horn
Amplifier type	cryo HEMT	cryo HEMT
T_{sys} (K)	40	42
S_{SEFD} (Jy)	1400	1050
PSS (Jy/K)	35	25
3 dB beamwidth (°)	0.16	0.57

Table 3 Parameters of the 26-m receiver (degraded performance due to dichroic reflector being used for simultaneous S-X VLBI).

Parameter	X-band	S-band
Feeds	dual CP conical	dual CP conical
Amplifier type	cryo HEMT	cryo HEMT
T_{sys} (K)	52	40
S_{SEFD} (Jy)	849	1190
PSS (Jy/K)	16.3	29.8
3 dB beamwidth (°)	0.096	0.418

3 Current Status

Telescope time allocation for geodetic VLBI consisted of 29 sessions on the 26-m antenna during 2015 and 33 sessions during 2016. The 15-m antenna participated in 153 sessions in 2015 and in 37 sessions in 2016 (Table 4). The 15-m antenna could not participate in a further 73 sessions scheduled from the 8th of February to the 11th of October 2016 due to a major antenna azimuth drive failure just before the start of the R1726 session. The azimuth motor-gearbox assembly was severely damaged during an electrical storm preceding the session. The rotor of the drive motor had disintegrated, and the gearbox was also damaged. A custom-built replacement motor-gearbox assembly had to be procured from Germany but got lost between the factory and the observatory, delaying the 15-m antenna's return to action by several weeks, with its first session after repairs, R4761 on the 13th of October 2016, being run in tag-along mode. Before this session, the 15-m antenna's S/X receiver was refurbished. Further extensive maintenance and refurbishment took place while the 15-m antenna was not operational. A reflector surface repair process was initiated in order to repair dry patches on the 15-m antenna's surface causing water ingress (see Figure 3).

Intermittent phase-cal and LO instability, during March–May 2015, pointed at possible damage to the 15-m antenna's cables through the wraps. New cables were installed in the azimuth wrap before the R4695 session on the 9th of July 2015. During August 2016, the 26-m antenna also displayed intermittent phase-cal and cable-cal values due to a loose connection in the cable between the antenna and the ground units.

During February and June 2015, the 15-m antenna participated in two AUSTRAL-CONT campaigns. Five experiments with both the 15-m and 26-m antennas observing—three R1s and two T2s—were performed during 2015, whilst only a single dual R1 session was possible during 2016. The 15-m antenna partcipated in one Chinese Lunar Lander Chang'E-3 RD/OCEL session during 2015 while the 26-m antenna observed in three such sessions in 2015 and four OCEL sessions in 2016. Geodetic VLBI data for all sessions were e-transferred to the correlators.

HartRAO has also been running astrometric single-baseline VLBI sessions in collaboration with Hobart (UTAS) to help to improve the S/X- and K-band reference frames in the South and its contribution to the ICRF-3. The 26-m antenna's sensitivity at 22 GHz has been improved by a factor of five with the installation of a cooled K-band receiver. The efficiency was doubled with a recent first-ever K-band session in the South at 2 Gbps. The combined upgrades enable the instrument to be used effectively at 22 GHz, tripling the resolution of the instrument over previous work at 8.4 GHz.

Table 4 Geodetic VLBI experiments in which HartRAO participated during 2015 and 2016.

Experiment	No. of sessions on 15 m		No. of sessions on 26 m	
	2015	2016	2015	2016
R1	49	15	3	6
R4	49	16	0	0
AUST15	30	0	0	0
AUST	12	1	0	0
RD	1	0	9	12
T2	6	2	2	1
CRDS	0	0	6	6
OHIG	6	3	0	0
RDV	0	0	6	5
CRF	0	0	3	3
Total	153	37	29	33

4 Personnel

Table 5 lists the HartRAO station staff involved in geodetic VLBI. Jonathan Quick (VLBI friend) provides technical support for the Field System as well as support for hardware problems. Operations astronomer, Alet de Witt, provides support for astrometric VLBI and is a member of the ICRF-3 Working Group. Astronomy student, Sayan Basu, joined the geodetic VLBI team as a trainee operator at the start of 2015.

5 New Developments

At the end of 2015, MT Mechatronics was appointed as supplier for the new 13.2-m VGOS antenna at HartRAO. Design reviews were undertaken during March 2016. The antenna is currently being manufactured. Alliance Construction was appointed as the civil works contractor and started site preparations in September 2016. The first steps taken during civil works concerned the site layout—surveying the site perimeter, clearing the site and surrounds, and establishing a slight slope for rainwater to run away from buildings. Water and electricity have been connected to the site, and the site has been fenced off to control access. The anchorage ring was the first part to arrive on site and has been positioned and cast in place (see Figure 4). Live footage of the construction process is being captured by a webcam and can be accessed at: http://geodesy.hartrao.ac.za/site/en/geodesy-equipment/vgos-telescope/150-vgos-videos.html

The HartRAO engineering team is designing a new automated dichroic mirror system for the 26-m antenna. The current design, with the dichroic mirror located in the X-band beam and reflecting the S-band beam, is to be replaced by a design with a reversed configuration, with the S-band beam reflecting the X-band. The new setup will be much smaller than the current one and will be automated to move in and out of the beam with actuators.

A local automated site tie system is being installed at HartRAO (see Figure 5). It uses a Leica MS50 Multistation that is mounted on a reference pier, which has line-of-sight to all of the major geodetic systems on-site. This system will perform frequent automated measurements to determine daily ties at the mm-level.

HartRAO is now hosting a Russian satellite laser and radio ranging system ≪Sazhen-TM+OWS≫. Full functionality was achieved on 16 December 2016.

Table 5 Staff supporting geodetic VLBI at HartRAO.

Name	Function	Program
L. Combrinck	Program Leader	Geodesy
J. Quick	Hardware/ Software	Astronomy
S. Basu	Operator	Student
R. Botha	Operator	Geodesy
J. Grobler	Operator	Technical
P. Mey	Operator	Geodesy
R. Myataza	Operator	Technical
M. Nickola	Logistics/ Operations	Geodesy
P. Stronkhorst	Operator	Technical
C. Zondi (2015)	Operator	Technical

HartRAO is continuing with its project to install GeoStations in the southern African regions as well as in the rest of Africa. These GeoStations consist of a GNSS reference station, seismometer, Met4 unit, and other equipment as required. HartRAO, Matjiesfontein, and the Nelson Mandela Metropolitan University (see Figure 6) already have such installations. A seismometer has been installed on Marion Island.

HartRAO in collaboration with the Namibian Port Authority, Namport, has installed GNSS reference stations at Lüderitz (see Figure 7) and Walvis Bay in Namibia on behalf of the University of Luxembourg. These installations are co-located with the tide gauges that were already operating there.

As part of the development of the new Lunar Laser Ranger, a new model of a timing reference system was developed by Microsemi according to our specifications. HartRAO has obtained the first such unit. It was characterized, and we are satisfied that it meets our system design requirements.

6 Future Plans

Of the 159 geodetic VLBI sessions scheduled for 2017, 127 sessions are allocated to the 15-m antenna with the remaining 32 sessions to be run on the 26-m antenna. The 15-m antenna will participate in several astrometric AUSTRAL sessions as well as in the CONT17 campaign taking place during November and December 2017.

Regarding VGOS activities, network and maser connections should be in place by February 2017. The last concrete pour is scheduled for 23 January 2017 with the last outstanding items being completed by the end of February 2017. Factory Acceptance Tests (FATs) for the VGOS antenna's steel top structure, i.e., everything from the azimuth cabin to the subreflector, are scheduled for mid-January 2017 at the CETC 54 facilities in China. The FAT for the hexapod and servo cabinets will follow in February 2017. After the FAT, the antenna will be shipped to HartRAO. Assembly is foreseen to start in April/May 2017 with final commissioning to take place around September 2017.

The total station should be operational by mid-2017. ≪Sazhen-TM+OWS≫ should also achieve full operational status by mid-2017.

The following GeoStation installations are to occur during 2017: at the Gamsberg in Namibia, Kutunse in Ghana, Necsa near HartRAO, and Klerefontein near the SKA core in South Africa. Stations are also planned for the Stellenbosch area in South Africa and Zambia.

During 2017, integration of all LLR hardware via a software system will be pursued. It is also endeavoured to procure the last few outstanding specialized hardware items for the LLR, such as the photon detection system.

Acknowledgements

HartRAO is a National facility operating under the auspices of the National Research Foundation (NRF), South Africa. The Space Geodesy Programme is an integrated program, combining VLBI, SLR, and GNSS, and it is active in several collaborative projects with GSFC, JPL, GFZ (Potsdam), and ≪Roscosmos≫ as well as numerous local institutes. Collaboration also includes OCA/NASA and the ILRS community in a Lunar Laser Ranger (LLR) project with local support from the University of Pretoria, amongst others. General information as well as news and progress on geodesy and related activities can be found at `http://geodesy.hartrao.ac.za/`.

Fig. 2 Thanking organizers and participants alike for making the 9th IVS GM hosted by HartRAO in March 2016 a great success!

Fig. 3 The surface of the 15-m antenna under repair: vacuum and fiberglass curing in progress. Visiting scientists beware—you will be put to work!

Fig. 4 VGOS site, 15 December 2016; last concrete pour of antenna tower is scheduled for the end of January 2017.

Fig. 5 The local automated site tie system is nearly ready to start operations.

Fig. 6 NMMU GeoStation installation, Port Elizabeth, South Africa.

Fig. 7 GNSS reference station and tide gauge at Lüderitz in Namibia.

AuScope VLBI Array and Hobart 26-m Antenna

Jim Lovell, Jamie McCallum, Lucia Plank, Brett Reid, John Dickey, Simon Ellingsen, Stas Shabala

Abstract This is a report on the activities carried out at the University of Tasmania in support of the three AuScope VLBI observatories and the Hobart 26-m antenna in 2015 and 2016. We describe our operations and research activities which are primarily focused on southern hemisphere priorities in geodesy and astrometry, as well as developing new techniques where a single-institute operated VLBI array such as ours can be used to great advantage.

1 General Information

As part of AuScope (www.auscope.org.au), the University of Tasmania (UTAS) operates the AuScope VLBI Array (Lovell et al., 2013), three 12-m diameter radio telescopes on the Australian continent, located near Hobart (Tasmania), Yarragadee (Western Australia), and Katherine (Northern Territory).

2 Staff

The staff at UTAS consists of academics, Prof. John Dickey (director), Dr. Simon Ellingsen, Prof. Peter McCulloch, and Dr. Stas Shabala. Dr. Jim Lovell is Project Manager for the AuScope VLBI project. Dr. Jamie McCallum, Dr. Lucia Plank, and Dr. Elizaveta Rastorgueva-Foi (until mid-2015) are post-doctoral fellows who are carrying out research aimed at improving geodetic solutions in the southern hemisphere. Mr. Brett Reid is the Observatory Manager whose position is funded by the University. Ms. Imogen Jones (until mid-2015) and Dr. Warren Hankey are employed to assist in operations and media logistics in particular. In addition we have an electronics technical officer, Mr. Eric Baynes. For operation of the observatories during geodetic observations we rely heavily on support from astronomy PhD and post graduate students. Logistical and maintenance support at Katherine is provided by Mr. Martin Ephgrave and Mr. Mick Stone and at Yarragadee by Mr. Randall Carman and team at the MOBLAS5 SLR station.

School of Mathematics and Physics, University of Tasmania

Hobart 12 m and 26 m, Katherine, and Yarragadee

IVS 2015+2016 Biennial Report

3 Current Status and Activities

From late July to early November 2015, a prototype broadband receiver system from Callisto was installed on the Hobart 12 m for testing. During that time, the Hobart antenna was not able to participate in regular IVS observations, so the Hobart 26-m telescope participated instead. This is reflected in the lower than usual number of observing days for Hobart 12 m and the higher than usual number for the 26 m.

Mechanical assessments by Challenger Communications were carried out in February 2016 on all three 12-m antennas. In general, the telescopes were found to be in good condition, and Challenger made some recommendations for ongoing maintenance activities. However, at Yarragadee some damage was found in the elevation jack-screw thread. This was probably caused when sand got into the grease as the result of a tear in the boot that surrounds it. The jackscrew will be replaced in the first half of 2017.

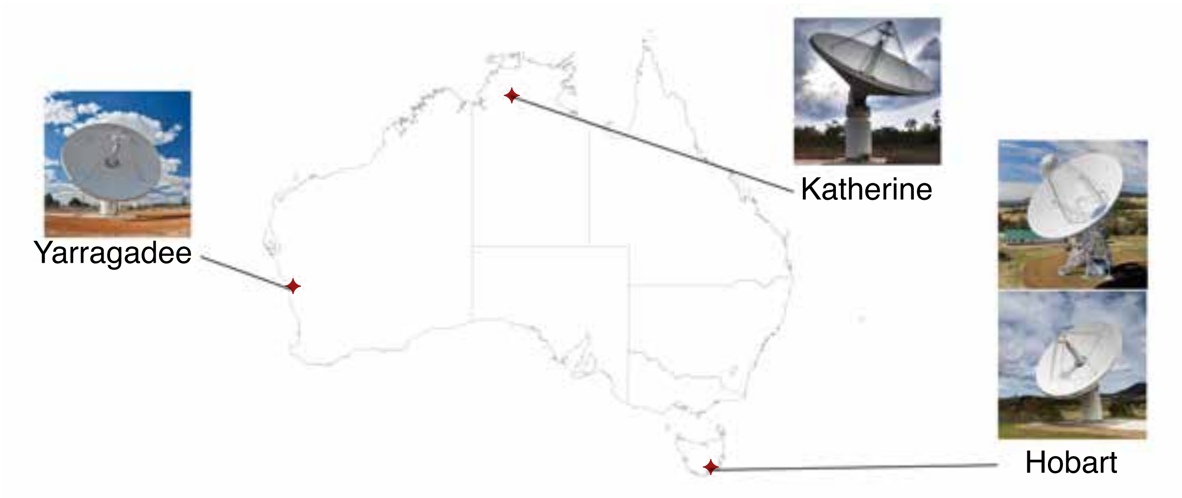

Fig. 1 The AuScope VLBI array and Hobart 26 m.

From mid-April to late May 2016, a major overhaul and maintenance was carried out on the Katherine and Yarragadee hydrogen masers by the manufacturer, Vremya-ch. Similar work was completed on the Hobart maser in October and November.

The Hobart 12 m was not used between June 3 and August 23, 2016 as it was occupied with further testing of the prototype Callisto broadband system. The Hobart 26 m was substituted for several of the experiments missed by the 12 m to compensate as much as possible. Testing with the Callisto system culminated in a successful broadband VLBI experiment with Ishioka and Kashima.

A representative from Intertronic Solutions visited the Hobart observatory in November to inspect and measure the pedestal of the 12-m antenna in preparation for the replacement of the cable wrap mechanism to occur in the first half of 2017.

In 2015, we also hosted two international meetings, the DiFX Users Meeting and the first Asia-Oceania VLBI Group (AOV) Meeting: "A Vision for Science and Technology with the AOV".

4 Geodetic VLBI Observations

In 2015 and 2016, the AuScope and Hobart 26-m antennas participated in 181 and 166 IVS sessions respectively (compared to 185 in 2014, 111 in 2013, and 72 in 2012) for a total of 509 and 414 antenna days respectively. A summary of the observations is presented in Tables 1 and 2.

Table 1 AuScope and Hobart 26-m antenna participation (number of days) in IVS sessions in 2015. The AUST15 series of observations were two 15-day CONT-like sessions as part of the AUSTRAL program.

Session	Antenna				Total
	Ho	Hb	Ke	Yg	
AOV	1	4	6	6	6
APSG	1	1	2	2	2
AUST-AST	1	8	8	8	8
AUST-GEO	1	19	17	19	19
AUST15		30	30	30	30
CRDS	5	3	6	6	6
CRF		3	3	3	3
OHIG	1	3	6	6	6
R&D	9				9
R1	15	25	43	42	45
R4	12	28	44	44	44
T2		2	3	3	3
Total	46	126	168	169	181

4.1 The AUSTRAL Program

The AUSTRAL Program commenced in July 2013. Observations are being made with the three AuScope antennas as well as the Warkworth 12 m and the Hartebeesthoek 15 m. The Hobart 26 m and the Harte-

Table 2 AuScope and Hobart 26-m antenna participation (number of days) in IVS sessions in 2016.

Session	Antenna				Total
	Ho	Hb	Ke	Yg	
AOV	2	4	5	5	6
APSG		1	2	2	2
AUST-AST	4	5	6	6	7
AUST-GEO	8	12	15	15	15
AUST-HOB	8	8			8
CRDS	6	5	5	5	6
CRF	3	2	3	3	3
OHIG		6	5	6	6
R&D	9	1			10
R1		36	39	42	49
R4		35	37	38	47
T2		6	7	7	7
Total	40	121	124	129	166

beesthoek 26 m also participate for some AUSTRAL sessions. Scheduling and correlation activities are shared between UTAS, Vienna, and Shanghai (the Curtin University software correlator was used until mid-2015).

As in previous years, the AUSTRAL observing program is focused on high priority geodetic and astrometric aims in the southern hemisphere:

1. astrometric observations to monitor and enhance the southern hemisphere reference frame in preparation for ICRF3;
2. regular observations to improve the density of the geodetic time series for the southern antennas and to measure and monitor the motion and deformation of the Australian plate;
3. four 15-day CONT-like sessions over two years to demonstrate the full capabilities of the array, characterize the level of systematic errors caused by the troposphere and source structure, and develop and try error mitigation strategies. One session was held in 2013, another in 2014, and two in 2015.
4. In 2016 we introduced eight HOB sessions that are aimed at understanding the tie between the new 12-m AuScope and "legacy" 26-m antennas at Hobart.

All AUSTRAL data are post-processed at UTAS and submitted to IVS as version 1 databases.

4.2 K-band Astrometry on the Hobart — Hartebeesthoek Baseline

The Hobart 26 m was involved in a number of single-baseline K- and X-band observations with the Hartebeesthoek 26-m telescope.

Observations are planned ahead of time with both K- and X-band schedules with X-band as a back-up in the event of poor weather at one or both sites. Observations are carried out using DBBC2 backends, utilizing the 2 Gbps capable v105E firmware. The K-band observations have largely been aimed at expanding the K-band catalog in the Southern polar cap. Only test observations in X-band have been carried out as yet.

The results from the first series of experiments have been processed and have yielded good results. Further observations are planned for 2017 and beyond.

5 Research Activities

We have now reached the critical mass to perform more research. Most of our activities are situated in the area of improved observations and operations. The easy access to a VLBI array and in particular the complete in-house capability, from scheduling to observations and all the way through to geodetic analysis, has proven very useful for our research activities, which are:

- **AUSTRAL Sessions.** The AUSTRAL program was mainly driven by the desire to improve geodetic results in terms of baseline repeatabilities. Efforts in scheduling, combined with the high data rate of 1 Gbps, have improved the results by a factor of two since the start of the program (Plank et al., 2016a). This program is evidence that research in the observing strategy pays off and that there is further room for improvement in our results.
- **South versus North.** North—South imbalance in the VLBI network has traditionally influenced our results. To mitigate these issues was one of the main justifications to build the AuScope array. In Plank et al., (2015) we could show that the regular participation of the AuScope telescopes in the IVS R1/R4 experiments had a clear impact on the results: in terms of baseline length repeatabilities, while previously the results were clearly worse for southern

baselines, one now finds repeatabilities comparable to those of northern baselines. This result and publication has helped to secure ongoing operation funds for the array.

- **Source structure simulations.** In collaboration with the Vienna group, a source structure simulator has been implemented in the Vienna VLBI Software (VieVS, Shabala et al., 2015). Performing simulations using the R1/R4 antenna network and observing schedules, we found that the systematic behavior of two component sources with low structure indices (1, 2) may have a significant impact on globally estimated source positions; while the larger additional delays due to source structure of nominally higher structure index (3, 4) are largely cancelled out in a global solution estimating source positions (Plank et al., 2016b).
- **Sibling telescopes.** The future operation of sibling and twin telescopes is another research area at UTAS. There were efforts in optimizing the scheduling of co-located telescopes (Plank et al., 2016c). A new scheduling mode was developed with the purpose of combining the AuScope 12-m telescope with the Hobart 26-m legacy antenna. This allows observations to much weaker sources (0.15 Jy), without decreasing the geodetic quality of the schedule (about 30 scans per hour per station). In 2016, four sessions (AUA009, AUA010, AUG024, and AUG026) were performed, observing 42 target weak sources that were selected by Karine Le Bail from GSFC.
- **VLBI satellite tracking.** This has been a major research focus during the last two years. Using UTAS operated telescopes in Ceduna (South Australia) and Hobart, the first VLBI time series of GNSS satellite observations was published (Plank et al., 2017). We particularly improved our knowledge about correlation and fringe fitting. In November 2016 intensive observations to the APOD satellite were done using the AuScope array. The observations are currently being correlated.
- **Dynamic Observing.** Being the most busy telescopes in the IVS, we always seek improvements in operation and automation. When operating an array, it is sad to see the telescopes resting on the weekends. This started the dynamic observing project. We have developed multiple routines that allow us to automatically schedule, download the schedule, start an experiment, and observe whenever a telescope is put as available for the dynamic observing (Lovell et al., 2016). Several DS experiments were run during weekends in 2016, also including the Hartebeesthoek 15-m telescope. We now seek more participants for a more global network. This will be further emphasized through some simulation results soon.

6 The Future

In 2017, the AuScope array will commence an upgrade to VGOS capability. This will include installation of Callisto Stirling-cycle cooled receivers with QRFH feeds, new DBBC3 systems, and FlexBuff recorders. The Hobart site will be upgraded first and the entire system tested and debugged before duplication and deployment at Katherine and Yarragadee. It will be important to stage the upgrade to maintain good global IVS array geometry during the transition from legacy to VGOS.

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Kashima 34-m VLBI Network Station Report for 2015—2016

Mamoru Sekido, Eiji Kawai

Abstract The NICT Kashima 34-m diameter radio telescope has been regularly participating in VLBI sessions organized by the IVS with a standard S/X band receiver. The station is maintained by the VLBI group of the Space Time Standards Laboratory of NICT. VLBI applications for precision frequency transfer form the main project of this group. A broadband feed with a narrower beam width was originally developed for the 34-m antenna, with Cassegrain optics. Broadband VLBI experiments for the evaluation of the receiver and the data acquisition system have been conducted with the NICT Kashima 34-m antenna, the GSI Ishioka 13-m station, and two small diameter VLBI stations located at NMIJ (Tsukuba) and NICT (Koganei). In addition to geodetic and time transfer VLBI observations, the Kashima 34-m antenna has been used for astronomical VLBI observations with the radio telescopes of NAOJ and domestic universities and for single dish observations for Jupiter and Pulsar.

Fig. 1 The Kashima 34-m radio telescope.

1 General Information

The 34-m diameter radio telescope is maintained and operated by the VLBI group of Space Time Standards Laboratory (STSL) in the National Institute of Information and Communications Technology (NICT). It is located in the Kashima Space Technology Center (KSTC), which is at the east coast of the main island of Japan. The STSL includes the Japan Standard Time and the Atomic Frequency Standard groups. They are engaged in keeping the national time standard JST and in the development of an advanced optical frequency standard, respectively. The other group of STSL is working for frequency transfer by using communication satellites and GNSS observations. Our VLBI group is sharing the task of precision time transfer technique development by means of VLBI. A new broadband VLBI system is being developed for application of time transfer and to be compatible with the VGOS system for future joint observing.

NICT Space-Time Standards Laboratory/Kashima Space Technology Center

NICT Kashima 34-m Network Station

IVS 2015+2016 Biennial Report

Table 1 Antenna performance parameters of the Kashima 34-m telescope.

Receiver	Pol.	Frequency	SEFD [Jy]
L-band	RHCP/LHCP	1405-1440MHz 1600-1720 MHz	∼ 300
S-band	RHCP/LHCP	2210-2350 MHz	∼ 350
X-band	RHCP/LHCP	8180-9080 MHz	∼ 300
Wideband	V-Linear Pol.	3.2-11 GHz	∼ 1000 – 2000
K-band	LHCP	22 - 24 GHz	∼ 2000
Q-band		42.3-44.9 GHz	∼3000

2 Component Description

2.1 Receivers

The Kashima 34-m antenna has multiple receiver systems from 1.4 GHz up to 43 GHz. The performance parameters for each frequency are listed in Table 1. Receiving bands are changed by exchanging receiver systems at the focal point of the antenna. Each receiver is mounted on one of four trolleys, and only one trolley can be at the focal position. The focal point is adjusted by the altitude of the sub-reflector with five axis actuators.

Fig. 2 A broadband NINJA feed was installed in the receiver room of the Kashima 34-m telescope.

2.2 Data Acquisition System

Three types of data acquisition systems (DAS) have been developed and installed at the Kashima 34-m station.

K5/VSSP32 is a multi-channel data acquisition system with a narrow frequency width up to 32 MHz [1]. One unit of the K5/VSSP32 sampler (Figure 3) has four analog inputs. Analog data is digitized by 64 MHz sampling rate in the first stage, then frequency shaped by digital filter at the second stage. A variety of sampling rates (0.04 – 64 MHz) and quantization bits (1 – 8 bit) are selectable. Four units of K5/VSSP32 compose one set of geodetic VLBI DAS with 16 video channels. Observed data is recorded in K5/VSSP data format. Software tools for observation and data conversion to Mark 5A/B format are freely available. Please visit the Web site[1] for details on K5/VSSP sampler specifications and software resources.

Fig. 3 One unit of K5/VSSP32 sampler has four video signal inputs. Data output and remote control is made via USB2.0 interface. One geodetic terminal of 16 video signals is composed of four units of this device.

K5/VSI is a data recording system composed of a computer with a ‘PC-VSI’ data capture card, which receives a VSI-H data stream as input and transfers it to the CPU of the computer via a PCI-X interface (Figure 4). Thanks to the standardized VSI-H interface specification, this system can be used to record any data stream of the VSI-H interface[2]. The NICT Kashima 34-m station is equipped with three kinds of VSI-H samplers (ADS1000, ADS2000 [2], and ADS3000+ [3]). The ADS3000+ sampler is capable of both broadband observations

[1] http://www2.nict.go.jp/sts/stmg/K5/VSSP/index-e.html
[2] http://vlbi.org/vsi/

(1024 Msps/1ch/1bit, 128 Msps/1ch/8bit) and multi narrow channel observing by using the digital BBC function, where one of the 2, 8, 16, or 32 MHz video band widths can be selected.
The K5/VSSP32 samplers and analog frequency video converter had been used for observing IVS sessions at NICT. Since 2016, the Kashima 34-m station has begun to use ADS3000+ with the DBBC function for IVS sessions.

Fig. 4 Upper panel shows PC-VSI card, which captures VSI-H data stream. Up to 2048 Mbps data stream is captured by one interface card. Lower panel shows ADS3000+, which is capable to extract 16 channels of narrow band signals via DBBC function, and it outputs data stream though VSI-H interface.

K6/GALAS is the new high speed sampler for the broadband VLBI observation project GALA-V [4]. Analog input data are converted to digital data at a 16.384 GHz sampling rate. Four digital data streams of 1024 MHz frequency width at requested frequencies are extracted by digital frequency conversion and the filtering function of the sampler. Output data comes out via a 10 Gbit-Ethernet interface in VDIF/VTP/UDP packet streams. A new aspect of K6/GALAS is so called 'RF-Direct Sampling', in which a radio frequency (RF) signal is directly captured without frequency conversion. This 'RF-Direct Sampling' technique has advanced the characteristic of precision delay measurements by VLBI.

3 Staff

Members who are contributing to maintaining and running the Kashima 34-m station are listed below in alphabetical order:

- HASEGAWA Shingo is the supporting engineer for IVS observing preparation and maintenance of file servers for e-VLBI data transfer.
- ICHIKAWA Ryuichi is in charge of maintaining GNSS stations.
- KAWAI Eiji is the main engineer in charge of hardware maintenance and the operation of the 34-m station. He is responsible for routine geodetic VLBI observations for IVS.
- KONDO Tetsuro maintains the K5/VSSP software package and is working to implement the ADS3000+ control function in FS9.
- SEKIDO Mamoru is responsible for the Kashima 34-m antenna as the group leader. He maintains the FS9 software for this station and operates the Kashima and Koganei 11-m antennas for IVS sessions.
- TAKEFUJI Kazuhiro is a researcher using the 34-m antenna for the GALA-V project and the Pulsar observations. He worked on the installation of the broadband IGUANA and NINJA receivers and made the subreflector position adjustment and perfomance measurement of the new receiver.
- TAKIGUCHI Hiroshi is a researcher for analysis of T&F transfer and geodesy with GNSS observations.
- TSUTSUMI Masanori is the supporting engineer for maintenance of data acquisition PCs and the computer network.
- UJIHARA Hideki is a researcher designing the new broadband IGUANA-H and NINJA feeds.

4 Current Status and Activities

4.1 VLBI Sessions for IVS, AOV, and JADE

The Kashima 34-m station is participating in VLBI sessions (CRF, RV, T2, and APSG) conducted by IVS. The Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) has been established since 2014 and has started local VLBI sessions. The Kashima 34-m station has been participating in AOV sessions and JADE sessions, which are Japanese domestic VLBI sessions conducted by the Geographical Survey Institute (GSI) to maintain station coordinates. The JADE sessions were terminated in 2014.

As described above, the K5/VSSP32 or ADS3000+ data acquisition terminals were used for data recording in the K5/VSSP data format. To export data to a foreign correlator, the data is converted to Mark 5B format using tools from the K5/VSSP package. All of the data provision to the correlator is made by e-Transfer through data servers listed in Table 2. Thanks to collaboration with Research Network Testbed JGN, a 10 Gbps network connection is available to the Kashima Space Technology Center. The server *k51c* is able to transfer the data at 10 Gbps, although *k51b* is limited to 1 Gbps due to the network interface card in it.

Table 2 VLBI data servers for exporting data by e-Transfer to correlators.

Server name	Data capacity	Network Speed
k51b.jp.apan.net	27 T Byte	1 Gbps
k51c.jp.apan.net	46 T Byte	10 Gbps

4.2 Broadband VLBI Experiments

The main mission of the VLBI project of NICT is the development of broadband VLBI systems for the application of distant frequency transfer. This project, named GALA-V [4], is targeting making a precision frequency comparison between small diameter VLBI stations which are equipped with a broadband VLBI observation system compatible with VGOS. The originally developed broadband IGUANA-H feed [5] was mounted at the end of 2013, and the first international VLBI observing was successfully performed with Haystack Observatory in January 2014. Another broadband NINJA feed was mounted at the 34-m telescope in July 2014. Then the frequency range 3.2 — 13 GHz became available. VLBI experiments for the development of a data acquisition system and signal processing were conducted with GSI's Ishioka 13-m station in the summer of 2015 and 2016. Wideband bandwidth synthesis software [6] was developed, and sub-picosecond precision delay measurement was achieved by the broadband system. A series of test VLBI sessions over 24 hours long was conducted with the GALA-V system in 2016. More details about the observations and an example of the results are reported in the "NICT VLBI Analysis Center Report" [7].

4.3 Observations under Collaborations

In collaboration with the National Astronomical Observatory of Japan (NAOJ) and domestic universities, this 34-m radio telescope has been used for VLBI observations and single dish observations.

Pulsar observations: In collaboration with Prof. Terasawa of RIKEN Japan, Tohoku University, and JAXA, multi-frequency observations of the Crab pulsar have been conducted [8]. The Kashima 34-m antenna has been used for this observing with an L-band receiver.

Jupiter Observations: For the investigation of Jovian Synchrotron radiation, the S-band receiver of the Kashima 34-m antenna has been used.

Astronomical VLBI Observations: Under collaboration with NAOJ, Yamaguchi University, Ibaraki University, and Tsukuba University, the Kashima 34-m station is participating in domestic astronomical VLBI observing with its X-band, K-band, and Q-band receivers.

5 Future Plans

Implementation by Dr. T. Kondo of remote setup and data recording control over ADS3000+ from FS9 is in progress. This might be supported in the standard FS9 release in the future.

Progression of corrosions at the backup structure of the 34-m station was found in 2016. Repair work as a counter measure to the corrosion is being planned for some months in the latter half of 2017.

Acknowledgements

We thank the research network JGN for supporting the network environment in this project.

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Kokee Park Geophysical Observatory

Chris Coughlin

Abstract This report summarizes the technical parameters of the VLBI systems at the Kokee Park Geophysical Observatory and provides an overview of the activities that occurred in 2015–2016.

1 Location

The Kokee Park Geophysical Observatory (KPGO) is located in Kokee State Park on the island of Kauai in Hawaii at an elevation of 1,100 meters near the Waimea Canyon, often referred to as the Grand Canyon of the Pacific. KPGO is located on the map at longitude 159.665° W and latitude 22.126° N.

2 Technical Parameters

The 20-m receiver is of NRAO (Green Bank) design (a dual polarization feed using cooled 15 K HEMT amplifiers). The antenna is of the same design and manufacture as those used at Green Bank and Ny-Ålesund. A Mark 5B+ recorder is currently used for all data recording.

The 12-m receiver is of MIT design. The ultra wideband receiver uses a Quadruple-Ridged Flared Horn (QRFH) and LNAs, developed at the California Institute of Technology, cooled to $\sim$15K and is dual polarization. The antenna is a prototype that was developed by InterTronic Solutions Inc. A Mark 6 recorder is currently used for all data recording.

Timing and frequency is provided by a Sigma Tau Maser with a NASA NR Maser providing backup. Monitoring of the station frequency standard performance is provided by a CNS (GPS) Receiver/Computer system. The Sigma Tau performance is also monitored via the IGS Network.

3 Staff

The staff at Kokee Park consists of six full time people and one part time person employed by Harris Corporation under the SCNS contract to NASA for the operation and maintenance of the observatory. Chris Coughlin, Lawrence Chang, Kiah Imai, and Robert Christensen conduct VLBI operations and maintenance. Ben Domingo is responsible for antenna maintenance, and Amorita Apilado provides administrative, logistical, and numerous other support functions. Kelly Kim also supports VLBI operations and maintenance during 24-hour experiments and as backup support.

4 Mission Support

Kokee Park has participated in many VLBI experiments including IVS R4 and R1 experiments. KPGO also participates in the RDV, CRF, and OHIG experiments. KPGO averaged two experiments of 24 hour duration each week, with weekday Intensive experiments in 2015 and 2016.

1. USNO
2. NASA GSFC

Kokee Park Geophysical Observatory

IVS 2015+2016 Biennial Report

Fig. 1 Newly installed 12-m VGOS telescope at KPGO.

Fig. 2 KPGO site overview after installation of the 12-m, removal of the 9-m, and removal of the 7-m.

Kokee Park hosts other systems, including the following: a Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) beacon and remote control, a Quasi-Zenith Satellite System (QZSS) monitoring station, a Two-Way Satellite Time and Frequency Transfer (TWSTFT) relay station, and a Turbo-Rogue GPS receiver. Kokee Park is an IGS station.

5 Recent Activities

The installation of the InterTronic Solutions 12-m VGOS radio telescope started in May of 2015 and was completed in October of 2015. The MIT-designed 12-m broadband signal chain installation started in November of 2015 and was completed by February 2016. Fringe tests were successful with GGAO and Westford antennas after the installation was complete. Both the antenna system and the signal chain have suffered failures since installation. The system is currently undergoing endurance testing, problem detection, and problem resolution in an effort to get the 12-m system to a status where it can pass the operational readiness review (ORR) and join the VGOS observing schedule.

The KPGO 20-m telescope has been in service for 24 years and was able to get some much needed upgrades in 2016. In April of 2016 GD-MS, the manufacturer of the 20-m, arrived at Kauai and began the azimuth bearing replacement effort. Over a span of three months we removed the old azimuth bearing from the 20-m and installed a new azimuth bearing. This was done by constructing a very large steel jacking frame around the pedestal of the antenna and jacking the upper half of the antenna up 18″ with a large hydraulic jacking system. All internal cabling had to be removed to allow bearing removal and installation. Once the upper half of the antenna was jacked up off the bearing, a shelf system was installed to slide the old bearing out and the new bearing in with the assistance of a crane. Once the new bearing was in and the surface flatness was machined to an allowable threshold, the upper half of the antenna was lowered down onto the new bearing, and hardware was installed to secure all parts of the antenna again. During this effort we also installed new azimuth gearboxes, upgraded the azimuth cable wrap system, and cleaned up wiring configuration when re-installing cabling. Muliple system tests were performed afterwards to ensure correct operation.

USNO, MIT, KPGO, and DREN were able to work together to upgrade the KPGO e-transfer network and restore e-transfer capability at the site in February of 2016. The site is still limited to a 100 Mbps transfer rate due to its microwave link down the hill to PMRF. High speed fibers are currently being repaired by PMRF to replace the microwave link up the hill. Plans are to work with PMRF, Hawaii Internet Consortium (HIC), and DREN to see if we can get a dedicated fiber connection to KPGO for our e-transfer network. Current plans are to still make real-time VLBI data transfers from KPGO a reality.

From August of 2016 through the end of the year we performed a major site clean-up effort and electrical upgrade at KPGO. The NASA 9-m Unified S-band antenna was removed from the site, as well as all supporting sub-systems and cabling for the 9-m. We also removed other various unused systems at the site during this effort, including the 7-m antenna that sup-

Table 1 Technical parameters of the radio telescopes at KPGO.

Parameter	20-m	12-m
Owner and operating agency	USNO-NASA	USNO-NASA
Year of construction	1993	2015
Diameter of main reflector d	20 m	12 m
Azimuth range	$\pm 270^\circ$	$\pm 270^\circ$
Azimuth velocity	$2^\circ/s$	$12^\circ/s$
Azimuth acceleration	$1^\circ/s^2$	$1^\circ/s^2$
Elevation range	$\pm 90^\circ$	$\pm 90^\circ$
Elevation velocity	$2^\circ/s$	$6^\circ/s$
Elevation acceleration	$1^\circ/s^2$	$1^\circ/s^2$
Receiver System		
Focus	Primary Focus	Cassegrain
Receive Frequency	2.2–8.9 GHz	2–14 GHz
T_{sys}	40 K	40 K
$S_{SEFDRange}$	500–2000 Jy	1500–3000 Jy
G/T	40 dB/K	43 dB/K
VLBI terminal type	VLBA4	RDBE
Recording media	Mark 5B+	Mark 6
Field System version	9.11.7	9.12.2

ported the UH GOES-7 program, the old UH 3-m antenna system, and the VHF SATAN antenna system. All unused material in the site yard was also removed. Electrical panels that feed the site as well as the 20-m telescope were upgraded with new panels that meet current electrical code. This effort not only cleaned up the site but also cleared some of the horizon mask for the 12-m telescope to widen its usable azimuth range.

Fig. 3 20-m telescope azimuth bearing replacement effort.

Fig. 4 9-m telescope demolition effort, with the 20-m and the 12-m operating in the background.

6 Outlook

KPGO will continue with efforts to get the 12-m system through the operational readiness review and to a point where it can join the VGOS observing schedule full time. The hope is to resolve all issues and participate in the 2017 VGOS observing schedule. We will continue planning with USNO and MIT for upgrading the 20-m signal chain to the broadband front end and backend systems currently being stored at KPGO. Before installing the broadband receiver on the 20-m, the Apex Focus System will have to be replaced due to rust and inability to move. The replacement of the focus system is also being planned as part of the broadband upgrade for the 20-m system. Now that the high speed fibers up the hill are being repaired the hope is to negotiate a dedicated fiber line for KPGO e-transfer that will give us high speed e-transfer capability.

Kashima 11-m and Koganei 11-m VLBI Stations

M. Sekido, E. Kawai

Abstract The Kashima and Koganei 11-m stations have been used for participating in T2, CRF, and APSG sessions conducted by the IVS and AOV sessions organized in the Asia-Oceania region.

1 General Information

A pair of 11-m diameter antennas have been operated by the VLBI group of the Space-Time Standard Laboratory (STSL) of the National Institute of Information and Communications Technology (NICT). The Kashima 11-m antenna is located at Kashima Space Technology Center (KSTC), on the east coast of the Japanese main island. The Koganei 11-m antenna is located at the headquarters of the NICT in Tokyo (Figure 1). The 11-m VLBI antennas at Kashima and Koganei (Figure 2) have been regularly operated with two other stations for the monitoring of crustal deformation of the Tokyo metropolitan area (Key Stone Project) since 1995 [1]. After the KSP project terminated in 2001, two 11-m diameter antennas were transferred to Gifu University and Hokkaido University. The Kashima and Koganei 11-m stations remained and have been used for research and technology development by NICT.

These two stations had not participated in international geodetic observing until 2011. After the "Tohoku earthquake" occurred in March 2011, the Kashima and Koganei stations have been participating in international IVS-R1, T2, APSG, and AOV sessions.

NICT Space-Time Standards Laboratory/Kashima Space Technology Center

NICT KSP Network Station

IVS 2015+2016 Biennial Report

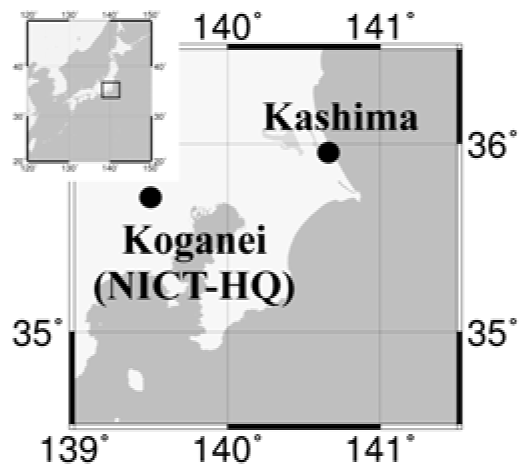

Fig. 1 Location of NICT-Koganei Headquarters and Kashima.

2 Component Description

2.1 Antenna

The antenna parameters of Kashima-11 and Koganei-11 are summarized in Table 1. The band-pass filters for S-band (2212–2360 MHz) were installed in 2010 at both stations for mitigation of radio frequency interference from cell phone stations. The local oscillator frequency of XH-band at the Kashima 11-m station has been changed from 7600 MHz to 7680 MHz since 2008, and since then, the observation bands of the Kashima and Koganei stations have been different by 80 MHz.

Fig. 2 11-m VLBI antennas at Kashima (left panel) and Koganei (right panel).

Table 1 The antenna parameters of the 11-m antennas.

		Kashima	Koganei
Antenna Type		Cassegrain type	
Diameter		11 m	
Mount Style		Az El mount	
Latitude		N 35° 57’ 19.46”	N 35° 42’ 37”.89
Longitude		E 140° 39’ 26.86”	E 139° 29’ 17”.06
Altitude		62.4 m	125.4 m
Rx Freq. [MHz]	S band	2212 ∼ 2360	2212 ∼ 2360
	X Low band	7700 ∼ 8200	7700 ∼ 8200
	X High band	8180 ∼ 8680	8100 ∼ 8600
Local Freq. [MHz]	S band	3000	3000
	X Low band	7200	7200
	X High band	7680	7600
SEFD [Jy]	X-band	5700	9500
	S-band	3300	5500

2.2 Data Acquisition Systems

Two kinds of samplers are available at both stations as summarized in Table 2. The K5/VSSP32 [2] has four channels of video band signal input per unit. Four units of K5/VSSP32 constitute one geodetic VLBI terminal with 16 video channels. This system is constantly used for geodetic VLBI observations including IVS sessions. This K5/VSSP32 sampler has digital filter functionality inside. The input video signal is digitized with 8-bit quantization with 64 MHz sampling. Then the frequency bandwidth is shaped by digital filter and output by specified data rate. The output data is written to a standard Linux file system in K5/VSSP32 format[1]. Data format conversion from K5/VSSP32 to Mark IV, VLBA, and Mark 5B are available with conversion tools[2].

Another sampler, ADS3000+ [3, 4], and a data recording system, PC-VSI, are available at both stations. The ADS3000+ sampler has the digital baseband conversion (DBBC) function, which enables flexible selection of 16 video frequency channels with any of the 4/8/16/32 MHz bandwidths. Thus, this is compatible with the conventional 16 channels of geodetic VLBI. Geodetic VLBI observing has been done by using K5/VSSP32, and ADS3000+ DAS is not used at the 11-m stations yet.

2.3 Network for e-Transfer

All of the data observed by the NICT VLBI stations are provided to the correlator by e-transfer. The acquired VLBI data format is converted to Mark 5B if necessary, and the data are put on external servers for e-transfer to the correlator. The speed of the local area network (LAN) connections among the Kashima 34-m, the Kashima 11-m, and the Koganei 11-m stations has

[1] Please see http://www2.nict.go.jp/sts/stmg/K5/VSSP/vssp32_format.pdf

[2] Observation and data conversion software for K5/VSSP are freely available from http://www2.nict.go.jp/sts/stmg/K5/VSSP/index-e.html

Table 2 VLBI data sampler/DAS systems equipped at the Kashima 11-m and Koganei 11-m stations.

System	K5/VSSP32 (4 units)	ADS3000+(K5/VSI)
Video Converter	K4/KSP 16ch	not necessary
# of Input Channels	4 /unit x 4 units	1 or 2
# of Output Channels	16	1, 2, 16
Input Freq. Range	0 - 300 MHz	0 - 2 GHz
Sampling Rate [Msps]	0.04,0.1,0.2,0.5,1, 2,4,8,16,32,64	128, 256, 1024, 2048,4096
Quantization bit	1,2,4,8 bit	
Max. data rate [Mbps]	256/unit x 4	4096
Output Interface	USB 2.0	VSI-H

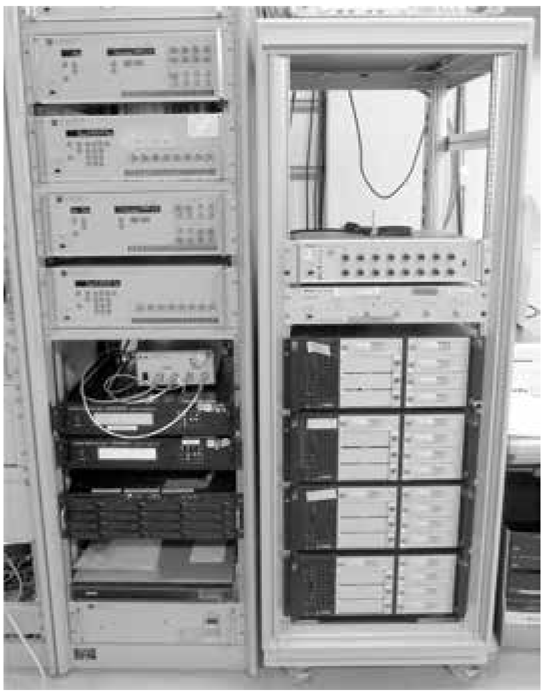

Fig. 3 Data acquisition terminal (K5/VSSP and K5/VSI) at the Kashima 11-m station.

been upgraded to 10 Gbps in 2014. The high speed network connection is provided by collaboration with the Research Network Testbed JGN. Figure 4 shows the schematic diagram of the local network connections and the outbound network.

2.4 GNSS Site

Both Kashima 11-m and Koganei 11-m have GNSS observation sites—named KSMV and KGNI, respectively. Their data is regularly uploaded to the International GNSS Service (IGS) Data Center. Figure 5 shows the KSMV station at the Kashima 11-m antenna site. A local survey was performed in 2014 at Koganei.

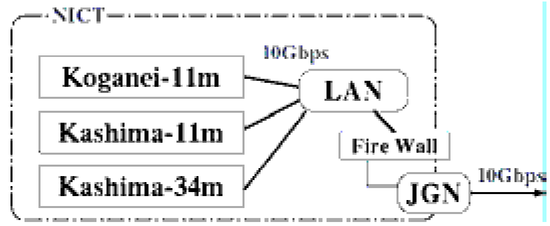

Fig. 4 The network environment of the NICT VLBI stations (Kashima 11-m, Kashima 34-m, and Koganei 11-m). A network speed of 10 Gbps is available internally and for e-transfer of VLBI data to the correlator.

Fig. 5 The Kashima 11-m antenna and the GNSS receiver pillar of the IGS tracking station KSMV.

3 Staff

The following staff members (in alphabetical order) are contributing to running the Kashima 11-m and Koganei 11-m stations.

Hasegawa Shingo: Supporting staff for IVS observing, operation of data conversion, and maintenance of file servers for e-transfer.

Ichikawa Ryuichi: In charge of GNSS station care and GNSS observations.

Kawai Eiji: In charge of station maintenance.

Kondo Tetsuro: Contributes to the implementation of ADS3000+ control by FS9. Maintains the K5/VSSP software package, which is used for data acquisition and conversion.
Miyauchi Yuka: In charge of data acquisition software with PC-VSI and VDIF data stream.
Sekido Mamoru: In charge of observing operations and overall activities of the Kashima and Koganei VLBI stations.
Tsutsumi Masanori: In charge of network security and maintenance of data acquisition computers.

4 Current Status and Activities during the Past Two Years

The Kashima and Koganei 11-m stations are participating in geodetic VLBI IVS-T2, APSG, CRF, and AOV sessions. Because of a system crash of the antenna control computer at the Kashima 11-m in 2016, some IVS sessions partially failed once. Except for that problem, the two stations have been working stably.

The Koganei 11-m antenna has been operated under time sharing with the Space Environment Laboratory (SPEL). Our group has higher priority to use the antenna for VLBI observing. When the antenna is free from VLBI observing, it is used for receiving a downlink signal from the STEREO satellite[3] by the SPEL.

The last pointing observation for upgrading the antenna axis parameter was made in January 2015.

Acknowledgements

We thank the research testbed network JGN and the Information System Section of NICT for supporting the high speed network environment.

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[3] http://www.nasa.gov/mission_pages/stereo/main/index.html

Matera CGS VLBI Station 2015–2016 Biennial Report

Giuseppe Bianco [1], Giuseppe Colucci [2], Francesco Schiavone [2]

Abstract This report presents the status of the Matera VLBI station. An overview of the station, some technical characteristics of the system, and staff addresses are also given.

1 General Information

The Matera VLBI station is located at the Italian Space Agency's 'Centro di Geodesia Spaziale G. Colombo' (CGS) near Matera, a small town in the south of Italy. The CGS came into operation in 1983 when the Satellite Laser Ranging SAO-1 System was installed. Fully integrated into the worldwide network, SAO-1 was in continuous operation from 1983 through 2000, providing high precision ranging observations of several satellites. The new Matera Laser Ranging Observatory (MLRO), one of the most advanced Satellite and Lunar Laser Ranging facilities in the world, was installed in 2002, replacing the old SLR system. CGS also hosted mobile SLR systems MTLRS (Holland/Germany) and TLRS-1 (NASA).

In May 1990, the CGS extended its capabilities to Very Long Baseline Interferometry (VLBI), installing a 20-m radio telescope. Since then, Matera has observed in 982 sessions up through December 2016.

In 1991, we started GPS activities, participating in the GIG 91 experiment and installing at Matera a permanent GPS Rogue receiver. In 1994, six TurboRogue SNR 8100 receivers were purchased in order to create the Italian Space Agency GPS fiducial network (IGFN). At the moment 12 stations are part of the IGFN, and all data from these stations, together with 24 other stations in Italy, are archived and made available by the CGS Web server GeoDAF (http://geodaf.mt.asi.it).

In 2000, we started activities with an Absolute Gravimeter (FG5 Micro-G Solutions). The gravimeter operates routinely at CGS and is available for external campaigns on request.

Thanks to the co-location of all precise positioning space-based techniques (VLBI, SLR, LLR, and GPS) and the Absolute Gravimeter, CGS is one of the few "fundamental" stations in the world. With the objective of exploiting the maximum integration in the field of Earth observations, in the late 1980s, ASI extended CGS' involvement to include remote sensing activities for present and future missions (ERS-1, ERS-2, X-SAR/SIR-C, SRTM, ENVISAT, and COSMO-SkyMed).

The Matera VLBI antenna is a 20-meter dish with a Cassegrain configuration and an AZ-EL mount. The AZ axis has ± 270 degrees of available motion. The slewing velocity is 2 deg/sec for both the AZ and the EL axes.

The technical parameters of the Matera VLBI antenna are summarized in Table 1.

The Matera time and frequency system consists of three frequency sources (two Cesium beams and one H-maser standard) and three independent clock chains. The iMaser 3000 H-maser from Oscilloquartz is used as a frequency source for VLBI.

1. Agenzia Spaziale Italiana
2. e-geos - an ASI/Telespazio company

Matera Network Station

IVS 2015+2016 Biennial Report

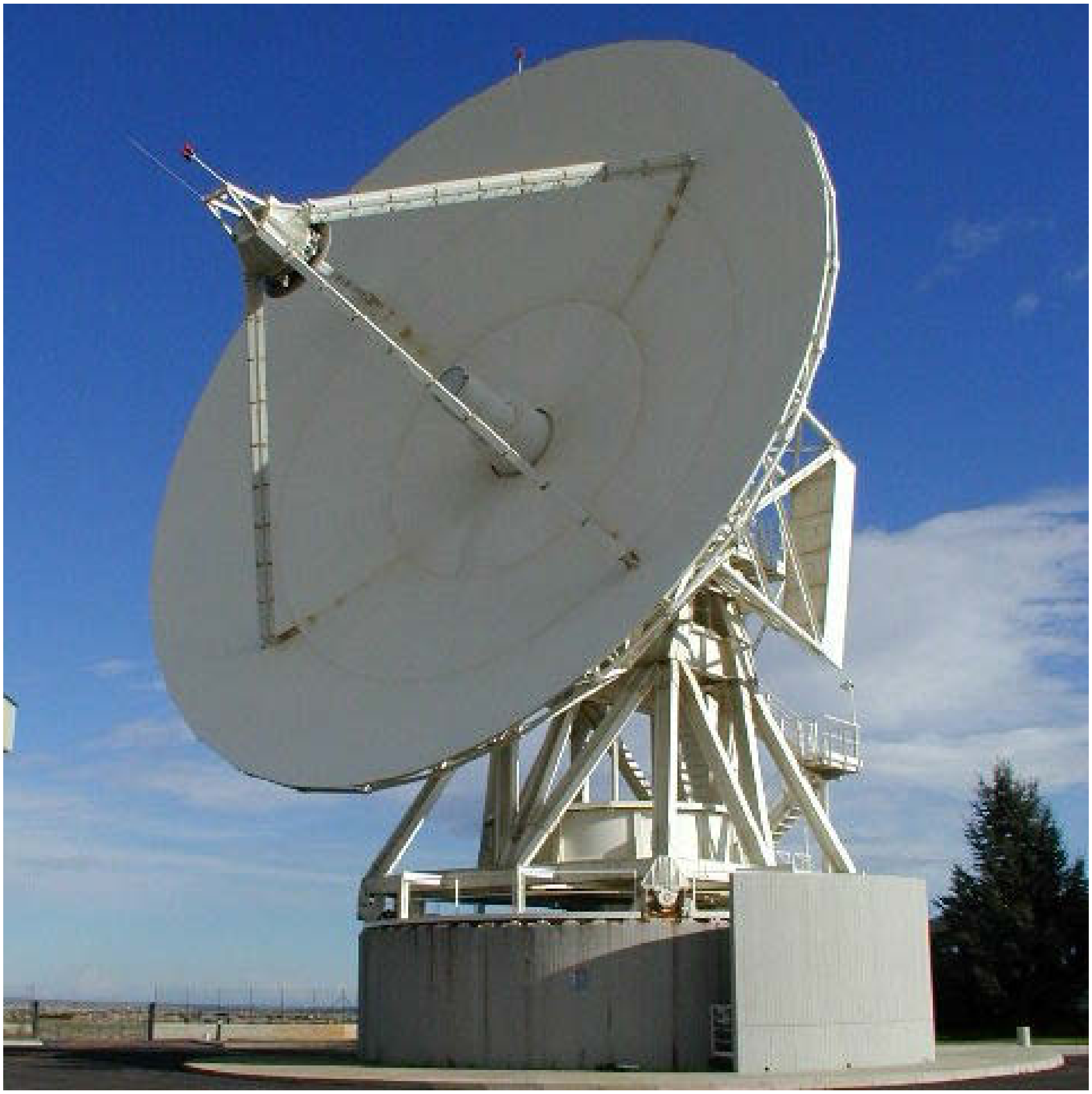

Fig. 1 VLBI antenna.

2 Activities during the Past Years

The VLBI frequency standard is a T4SCIENCE iMaser 3000 installed in 2013.

Specifications for this new maser can be found here: http://www.t4science.com/product/imaser_3000.

3 Current Status

In 2015 and 2016, 52 and 53 sessions were observed respectively. Figure 2 shows a summary of the total acquisitions per year, starting in 1990.

In 2004, in order to fix the existing rail problems, a complete rail replacement was planned. In 2005, due to financial difficulties, it was instead decided that only the concrete pedestal under the existing rail would be

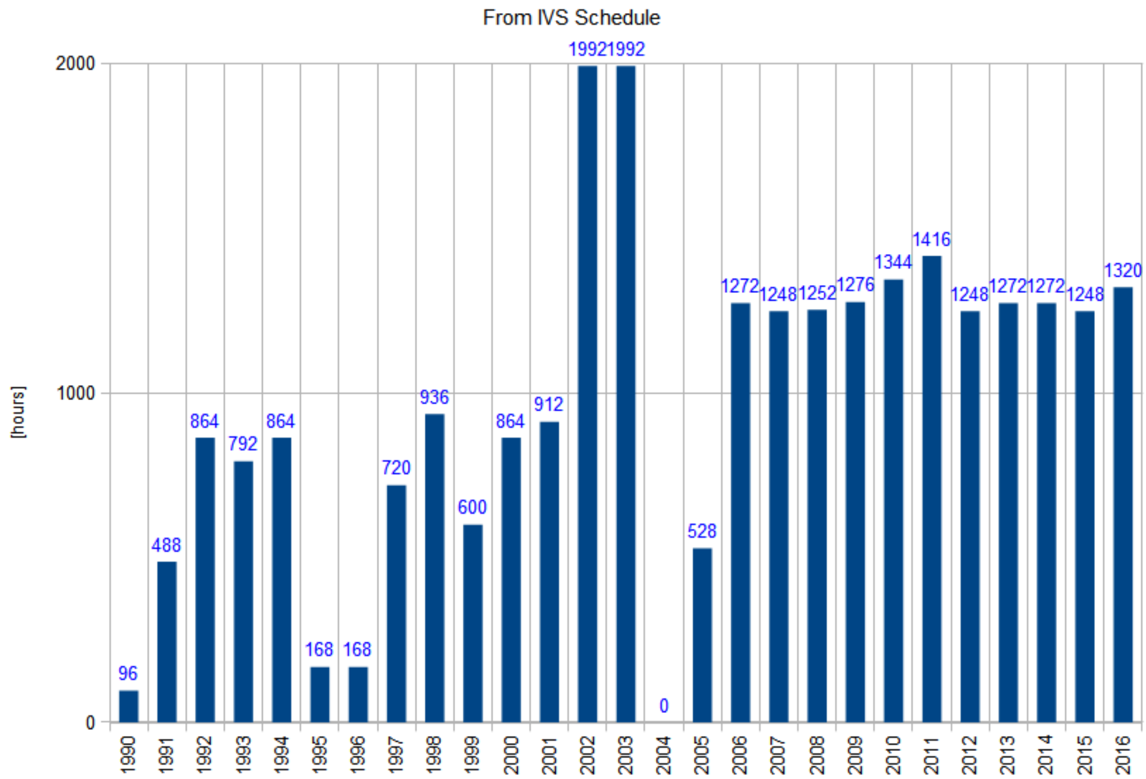

Fig. 2 Observation time.

Table 1 Matera antenna technical specification.

Parameter name	Values (S/X)
Input frequencies	2210−2450 MHz / 8180−8980 MHz
Noise temperature at dewar flange	<20 K
IF output frequencies	190−430 MHz 100−900 MHz
IF Output Power (300 K at inp. flange)	0.0 dBm to +8.0 dBm
Gain compression	<1 dB at +8 dBm output level
Image rejection	>45 dB within the IF passband
Inter modulation products	At least 30 dB below each of two carriers at an IF output level of 0 dBm per carrier
T_{sys}	55/65 K
SEFD	800/900 Jy

repaired. From then on, no rail movements were noted [1, 2, 3].

4 Future Plans

In order to plan the eventual building of a VGOS system, the fund raising investigation process has begun. Financing is on the first stage of ASI approval process.

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Medicina Station Status Report

Alessandro Orfei, Giuseppe Maccaferri, Andrea Orlati

Abstract General information about the Medicina Radio Astronomy Station, the 32-m antenna status, and the staff in charge of VLBI observations are provided. Updates to the hardware were performed and are briefly described.

1 The Medicina 32-m Antenna: General Information

The Medicina 32-m antenna is located at the Medicina Radio Astronomy Station. The station is run by the Istituto di Radioastronomia and is located approximately 33 km east of Bologna. The Consiglio Nazionale delle Ricerche was the funding agency of the Istituto di Radioastronomia until the end of 2004. Since January 1, 2005, the funding agency has been the Istituto Nazionale di Astrofisica (INAF). The antenna, which was inaugurated in 1983, has regularly taken part in IVS observations since 1985 and is an element of the European VLBI network.

A permanent GPS station (MEDI), which is a part of the IGS network, is installed in the vicinity. Another GPS system (MSEL) is installed near the VLBI telescope and is part of the EUREF network.

Istituto di Radioastronomia INAF, Medicina

Medicina Network Station

IVS 2015+2016 Biennial Report

2 Current Status and Activities

- Antenna — In May 2015 a long maintenance period was concluded by painting the antenna structure and by the restoration and painting of the antenna basement. The painting of the primary mirror surface is scheduled for 2017. The rail track is at the end of its life, showing cracks and wear. Its substitution is scheduled for 2017.
- VLBI back-end — The DBBC firmware version is currently DDC $V105_1$ and $V105_1E$, PFB $v15_2$. The release 2.8.0 of jiveab is currently installed. The purchase of a couple of flexbuff systems is scheduled in 2017. The overall system DBBC+FILA10G+Mark5C is running smoothly now; the VDIF data format was definitively adopted.
- e-VLBI — Medicina is routinely running e-VLBI experiments. The last update is that first fringes at 4 Gbit/sec in C band, 512 MHz dual polarization bandwidth, PFB firmware 32x32MHz, 2 bit sampling were obtained. DBBC proxy software was installed in our Mark5, but an APU system has been acquired.
- Field System — i) Many releases were installed in these last two years. We are currently running release 9.11.18; ii) jsched was installed and made available for the operators.

3 Geodetic VLBI Observations

In 2015–2016, Medicina participated in 42 24-hour routine geodetic sessions: 20 IVS-R4, six IVS-T2, seven EUROPE, seven R&D, and two VITA experiments.

Metsähovi Radio Observatory Network Station 2015–2016 Biennial Report

Guifré Molera Calvés [1], Nataliya Zubko [1], Juha Kallunki [2], Ulla Kallio [1], Kimmo Lehtinen [1], Markku Poutanen [1], Jenni Virtanen [1]

Abstract In 2015–2016, Metsähovi Radio Observatory, together with the Finnish Geospatial Research Institute, has observed seven IVS sessions: four T2 and three EUROPE sessions.

1 General Information

The Aalto University Metsähovi Radio Observatory and the Finnish Geospatial Research Institute (FGI) are two separate institutes which together form the Metsähovi IVS Network Station. Metsähovi Radio Observatory operates a 13.7-meter radio telescope on the premises of Aalto University at Metsähovi, Kylmälä, Finland, about 35 km from the university campus. The Metsähovi Fundamental Geodetic Station of FGI is in the same area, next to the Metsähovi Radio Observatory.

2 Component Description

FGI is responsible for the geodetic VLBI observations and is the owner of the S/X receiver. The radio telescope is owned and operated by the Aalto University, and an annual agreement is made on its use for geodetic VLBI sessions. It is not possible to increase the number of annual geodetic sessions (currently typically four) because the telescope is mainly used for astronomical observations.

1. National Land Survey of Finland, Finnish Geospatial Research Institute
2. Aalto University Metsähovi Radio Observatory

2.1 Metsähovi Radio Observatory

The Metsähovi Radio Observatory has been operational since 1974. The telescope was upgraded in 1992–1994. The radome was replaced with a new one, and new surface panels were installed. Metsähovi, together with FGI, began observing IVS T2 and EUROPE sessions in 2004. Approximately four to six sessions are observed per year.

Metsähovi is known for its long-term quasar monitoring, the VLBI and solar observations. The surface accuracy of the present telescope is 0.1 mm (rms) and the speed of the Metsähovi antenna is 1.2 degrees per second. Astronomical VLBI observations are carried out with the 22 GHz, 43 GHz, and 86 GHz receivers while the geodetic observations use the S/X narrow band receiver. The geodetic VLBI receiver uses right circular polarization and 8.15–8.65 GHz and 2.21–2.35 GHz frequency bands.

2.2 Metsähovi Geodetic Fundamental Station

FGI is running the Metsähovi Geodetic Fundamental Station. It is a part of the IAG GGOS Core station network. The instrumentation includes geodetic VLBI (in co-operation with Aalto University), Satellite Laser Ranging (SLR), DORIS, and GNSS equipment and absolute and superconducting gravimeters.

Fig. 1 A view of the Metsähovi Fundamental Geodetic Station. At the center of the picture is the new building of the SLR telescope. At right, the radome of the 13.7-m radio telescope of Aalto University can be seen.

Table 1 Staff at Metsähovi Radio Observatory and at FGI involved in geodetic observations during 2015–2016.

Staff at Metsähovi Radio Observatory		
Name	Title	Responsibility
Ph.D. Joni Tammi	Head of Metsähovi Radio Observatory	Metsähovi Radio Observatory
Ph.D., Lic.(tech.) Juha Kallunki	Technical staff manager	VLBI equipment and observations
M.Sc.(tech.) Ari Mujunen	Laboratory engineer	VLBI equipment
D.Sc.(tech.) Minttu Uunila (until 11/2015)	Post-doctoral researcher	VLBI observations
M.Sc.(tech.) Petri Kirves	Operations engineer	Receivers
Staff at Finnish Geospatial Research Institute		
Name	Title	Responsibility
Prof. Markku Poutanen	Head of the Department	Metsähovi research station
Ph.D. Jenni Virtanen	Research manager	Space geodesy research group
Ph.D. Jyri Näränen	Research manager	Metsähovi infrastructure
Ph.D. Nataliya Zubko	Senior research scientist	IVS observations, analysis; VGOS project manager
D.Sc. (tech.) Guifré Molera Calvés	VLBI technical expert	VLBI development
M.Sc. Veikko Saaranen	Special research scientist	IVS observations, operations
Adj. prof. Kimmo Lehtinen	Special research scientist	IVS observations, operations
M.Sc. Ulla Kallio	Senior research scientist	Local ties measurements

Currently, instrumentation is being renewed based on special funding from the Finnish Ministry of Agriculture and Forestry. During the years 2015–16, a new dome for SLR was constructed, and a new SLR telescope and optical instruments were installed. Currently, the system finalization is ongoing, and it is expected to be operational by 2018.

At the start of 2015, the Finnish Geodetic Institute became a part of the National Land Survey of Finland (NLS) as the Finnish Geospatial Research Institute (the abbreviation remaining FGI).

2.3 New Radio Telescope System

The Finnish Ministry of Agriculture and Forestry and NLS have granted FGI special funding to build a new radio telescope system which will be compatible with VLBI2010 Global Observing System (VGOS), the next-generation geo-VLBI observing technique. The VGOS project started with the tendering process for the new telescope in early 2016, and in December the contract was signed with the manufacturer; MT Mechatronics (Germany) is responsible for building and assembling the 13.2-m dish telescope. In addition to the telescope, an innovative signal chain will be built to meet the VGOS requirements. Once operational (first light expected by 2019), the telescope system is planned to be a part of the IVS network.

3 Staff

Operations during the geo-VLBI sessions and technical questions are handled jointly between Aalto University and FGI. All other technical work, telescope maintenance and maintenance of instrumentation are done by the Metsähovi Radio Observatory personnel. The preparation, operation of IVS observations, and submission of data are provided by staff from FGI. Personnel working with IVS observations are listed in Table 1.

4 Current Status and Activities

4.1 IVS Sessions

Metsähovi, together with FGI, observed altogether four IVS sessions during 2015: two T2 sessions (T2 105 and T2 108) and two EUROPE sessions (EUR 137 and EUR 138). During 2016, altogether three IVS sessions were observed: two T2 sessions (T2 110 and T2 111) and one EUROPE session (EUR 141). There were no technical issues or problems during the observations or correlations.

4.2 Research Visits

In preparation for the telescope tendering process in the VGOS project, Nataliya Zubko and Jyri Näränen visited the Onsala Space Observatory (Chalmers, Sweden) in October 2015. They also attended the 2nd IVS Training School on VLBI for Geodesy and Astrometry, March 9-12, 2016 (Hartebeesthoek, South Africa). Guifre Molera Calvés and Jyri Näränen visited the Onsala Space Observatory again in December 2016 to discuss the signal chain design for the VGOS project.

4.3 Technical Activities

The VLBI observations continued to be conducted using the DBBC. No problems were detected during the sessions.

Two new active hydrogen masers were delivered to Metsähovi in February 2015. One is working as a frequency reference for various VLBI devices, and the second one is working as a back-up frequency reference.

In June 2016, due to a heavy thunderstorm and lightning, the DBBC's 1pps distribution board (1pps TTL driver board MAX9372) broke. This was fixed locally in the observatory (July 2016).

In addition all the motors of the 13.7-meter radio telescope were replaced in January 2016.

4.4 Data Analysis

Data analysis at FGI was performed by Dr. Zubko. The project of source structure study and its influence on estimated geodetic VLBI parameters was continued in cooperation with Dr. Rastorgueva-Foi and Lucia Plank from University of Tasmania. The latest results on this research were presented at the 22nd EVGA Working Meeting in 2015 (Sao Miguel, Azores).

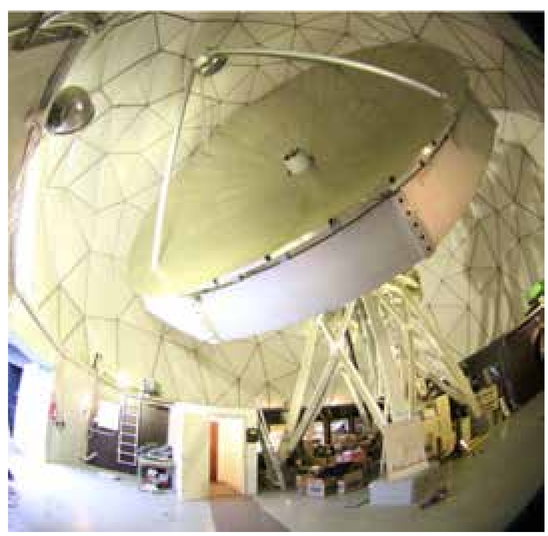

Fig. 2 Metsähovi radio telescope (Photo by Merja Tornikoski).

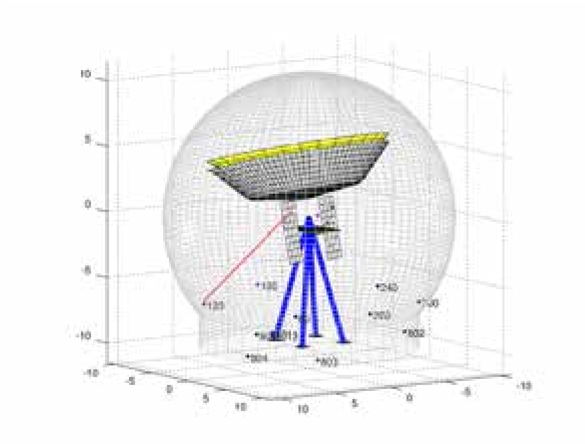

Fig. 3 Robot tachymeter aimings were precalculated and optimized using the antenna schedule file before the local tie measurement campaign.

4.5 Local Tie Measurements

In August and September 2015, Metsähovi participated in the EMRP SIB60 local tie experiment. With the co-operation of Frankfurt University of Applied Sciences, Laboratory for Industrial Metrology, SP Technical Research Institute of Sweden, Chalmers University of Technology, Onsala Space Observatory, two different local tie methods were used simultaneously for measurements of a VLBI baseline (Onsala-Metsähovi) and a GPS baseline between IGS points (ONSA-METS). Local ties were measured with robot tachymeters and with GNSS at Metsähovi and at Onsala at the same time. Monitoring measurements with robot tachymeters were performed using the HEIMDALL monitoring system (see Figure 3). The monitoring network under the radome was connected to the local pillar network at Metsähovi soon after the monitoring. Besides the dedicated campaign we reprocessed 25 GPS local tie vectors with new GPS antenna calibration values. During the SIB60 project we developed the new Monte Carlo based method to assess the uncertainty of GPS local ties. Besides the Monte Carlo method we assessed uncertainties using time series of GPS based local ties and the comparison of the local ties of the two methods. The realistically achievable uncertainty for the GPS local tie vector according to the assessment is 1 mm for the North and East components and 2 mm for the Up component.

5 Future Plans

In 2017 Metsähovi is scheduled to participate in four IVS sessions: two EUROPE sessions (EUR D01 and EUR D02) and two T2 sessions (T2 116 and T2 120).

The VGOS project at FGI will continue. The installation of the VGOS radio telescope at the Metsähovi Geodetic Fundamental Station is scheduled to start in April 2018. The location of the antenna has already been selected, less than 100 meters away from the FGI main building. Work for the site preparation has already begun with cutting out the forest area and will continue with foundation work during spring 2017.

VERA 2015 and 2016 Geodetic Activities

Takaaki Jike, Yoshiaki Tamura

Abstract The geodetic activities of VERA in the years 2015 and 2016 are briefly described. The regular geodetic sessions were observed both in K- and S/X-bands. The frequency of regular sessions is three times a month—twice for the VERA internal sessions in K-band. The networks of the S/X sessions are AOV and IVS-T2. The raw data of the T2 and AOV sessions are electronically transferred to the Bonn, SHAO, and GSI correlators via Internet. Gravimetric observing is performed at the VERA stations. SGs are installed at Mizusawa and Ishigakijima in order to monitor precise gravity changes, and the observations continued for two years.

Fig. 1 The front view is of the Mizusawa 10-m antenna, and the back view is of the VERA Mizusawa 20-m antenna.

1 General Information

VERA is a Japanese domestic VLBI network consisting of the Mizusawa, Iriki, Ogasawara, and Ishigakijima stations. Each station is equipped with a 20-m radio telescope and a VLBI back-end. The VERA Mizusawa 20-m antenna is shown in Figure 1. The VERA array is controlled from the Array Operation Center (AOC) at Mizusawa via Internet.

The primary scientific goal of VERA is to reveal the structure and the dynamics of our galaxy by determining three-dimensional force field and mass distribution. Galactic maser sources are used as dynamical probes, the positions and velocities of which can be precisely determined by phase referenced VLBI relative to extragalactic radio sources. The distance is measured as a classical annual trigonometric parallax. The observing frequency bands of VERA are S and X, C (6.4 GHz), K (22 GHz), and Q (43 GHz). Geodetic observations are made in S/X- and K-bands. Q-band is currently not used for geodesy. Only a single beam is used even in K-band in geodetic observations, although VERA can observe two closely separated ($0.2^\circ <$ separation angle $< 2.2^\circ$) radio sources simultaneously by using the dual beam platforms.

General information about the VERA stations is summarized in Table 1, and the geographic locations are shown in Figure 2. The lengths of the baselines range from 1,080 km to 2,272 km. The skyline at Ogasawara station ranges from 7° to 18° because it is located at the bottom of an old volcanic crater. The northeast sky at Ishigakijima station is blocked by a nearby high mountain. However, the majority of the skyline is below 9°. The skylines at Mizusawa and Iriki are low enough to allow sources to be observed at low elevations. Because Ogasawara and Ishigakijima are small

Mizusawa VLBI Observatory, National Astronomical Observatory of Japan

VERA Network Station

IVS 2015+2016 Biennial Report

islands in the open sea and their climate is subtropical, the humidity in the summer is very high. This brings about high system temperatures in the summer, in particular in K- and Q-bands. Iriki station as well as these stations are frequently hit by strong typhoons. The wind speed sometimes reaches up to 60–70 m/s.

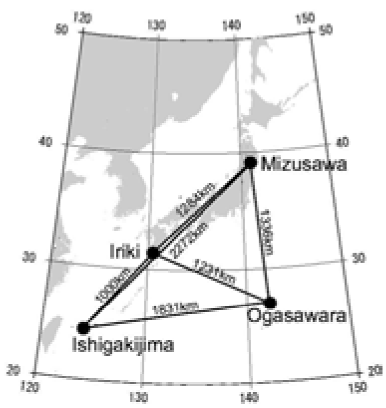

Fig. 2 Distribution of the stations in the VERA Network.

Table 1 Location.

Site name	Longitude	Latitude	Altitude
Mizusawa	141° 07' 57".199 E	39° 08' 00".726 N	75.7 m
Iriki	130° 26' 23".593 E	31° 44' 52".437 N	541.6 m
Ogasawara	142° 12' 59".809 E	27° 05' 30".487 N	223.0 m
Ishigakijima	124° 10' 15".578 E	24° 24' 43".834 N	38.5 m

2 Current Status

The parameters of the antennas and front- and back-ends are summarized in Tables 2 and 3, respectively. Two observing modes are used for geodetic observing. One is VERA internal observing in K-band with the recording rate of 1-Gbps. The other is conventional S/X-band observing with K5-VSSP. JADE, which is GSI's domestic observing project, and IVS-T2 sessions belong to this class. Only Mizusawa and Ishigakijima participated in these sessions.

Table 2 Antenna parameters.

Diameter of main reflector	20m		
Mount type	AZ-EL		
Surface accuracy	0.2mm (rms)		
Pointing accuracy	<12"(rms)		
	Azimuth	Elevation	
Slew range	-90° – 450°	5° – 85°	
Slew speed	2.1°/sec	2.1°/sec	
Acceleration	2.1°/sec^2	2.1°/sec^2	
	S	X	K
HPBW	1550"	400"	150"
Aperture efficiency	0.25	0.4	0.47

Table 3 Front-end and back-end parameters.

Front-end parameters			
Frequency band	S	X	K
Frequency range (GHz)	2.18–2.36	8.18–8.60	21.5–24.5
Receiver temperature	>100 °K	100 °K	39±8 °K
Polarization	RHC	RHC	LHC
Receiver type	HEMT	HEMT	cooled HEMT
Feed type	Helical array		Horn

Back-end parameters		
Observing type	VERA	T2, JADE, AOV
channels	16	16
BW/ch [MHz]	16	4 or 8
Filter	Digital	Analog video band
Recorder	OCTADISK	K5-VSSP
Rec. rate [Mbps]	1024	128
Deployed station	4 VERA	Mizusawa, Ishigakijima

3 Activities during the Past Two Years

VERA observes seven days a week, except for during a maintenance period from mid-June to mid-August. The 24-hour geodetic sessions are allocated two or three times in a month. Among these geodetic sessions, VERA internal geodetic sessions in K-band are performed once or twice in a month, and Mizusawa participates in JADE, AOV, or IVS-T2 sessions in S/X-band on a once-a-month basis. Ishigakijima participated in IVS-T2 or JADE sessions until February 2015. The main purpose of the VERA internal geodetic sessions is to determine the relative positions of the VERA antennas accurately enough for astrometric requirements. The purpose of the S/X sessions is to link the VERA coordinates into the IVS reference frame.

In the VERA internal geodetic sessions, the regularly-used frequency changed from S/X-band to K-band in 2007. The reason for the shift of the observing frequency band from S/X-band to K-band is to avoid the strong radio interference by mobile phones in S-band, particularly at Mizusawa. The interfering signal which has line spectra is filtered out. But this filtering considerably degrades the system noise temperature. The interference zone is increasing, so it is likely that S-band observing will become impossible in the near future. On the other hand, VERA has the highest sensitivity in K-band as shown in Table 3. Thanks to the high sensitivity in this band the maximum number of scans in K-band is 800/station/24-hours while that in S/X-band is 500 at most. It has been confirmed that the K-band observations are far more precise. In fact, standard deviations of the individual determinations of the antenna positions in K-band are less than half of those in S/X-band.

In 2015 and 2016, a long maintenance period from the middle of June to the middle of August was allocated for each year. Except for this period, VERA performed regular VLBI observing. Mizusawa participated in five T2 sessions, three JADE sessions, and two AOV sessions during 2015, and Ishigakijima participated in one JADE session and one T2 session in February 2015. In 2016, Mizusawa participated in five T2 sesions and three AOV sessions. VERA internal geodetic sessions were observed 15 times in 2015 and 18 times in 2016. The final estimates of the geodetic parameters are derived by using software developed by the VERA team.

Continuous GPS observing was performed at each VERA station throughout the year. The superconducting gravimeter (SG) installed within the enclosure of the Mizusawa VLBI observatory, in order to accurately monitor gravity change for the purpose of monitoring height change at the VERA Mizusawa station, continued acquisition of gravity data. Four water level gauges surrounding the SG were used for monitoring the groundwater level. The preliminary results show that gravity variation due to the variation of the water table can be corrected as accurately as the 1 micro gal level. An SG was newly installed also at the VERA Ishigakijima station, and observing started in January 2012. The observing continued also during 2015—2016. The observing aims at solving the cause of the slow slip event which occurs frequently around the Ishigaki island.

4 Staff

Mareki Honma is the director of the Mizusawa VLBI Observatory. The geodesy group consists of Yoshiaki Tamura (scientist) and Takaaki Jike (scientist).

5 State of the Crustal Movement after Earthquakes

After the 2011 earthquake off the Pacific coast of Tohoku (Mw=9.0) [Epoch=11 March 2011, 14:16:18 JST], Mizusawa was displaced by co-seismic crustal movement and post-seismic creeping. Also from 2015 to 2016, the creeping continued, although the speed declined. According to the newest analysis, the co-seismic steps are X= -2.062 m, Y= -1.416 m, and Z= -1.064 m, and the displacement by creeping during two years, 2015 and 2016, is X= -0.182 m, Y= -0.105 m, and Z= -0.036 m. Due to the 2016 Kumamoto Earthquake (Mw=7.0) [Epoch=14 April 2016, 01:25:05 JST], crustal deformation changed the position of Iriki. The displacement of Iriki by co-seismic step and post-seismic creeping due to the Kumamoto Earthquake is more than 1 cm towards the south in total.

6 Recording, Correlation, and Future Plans

In 2015, we replaced our 1-Gbps recording system with a Hard Disk Recorder (OCTADISK) and our correlator with a Software Correlator. The examination of increasing a recording rate to 8-Gbps from 1-Gbps by using a high speed sampler (OCTAD) is being performed. Experimental geodetic VLBI observing was performed in February 2016 using the high speed sampler, and we can get geodetic solutions. It is planned that OCTAD will be placed in all of the VERA stations starting in 2017 and afterwards. Reconstruction of the S/X system is also planned, in accordance with the change to the specification of international VLBI Experiments. The received frequency of X-band will be widened to 8-9 GHz.

Noto Station Status Report

Carlo Stanghellini, Pietro Cassaro

Abstract The Noto VLBI Station has been operational in the past two years, except for short periods of maintenance totaling two months. The current status of the antenna is provided.

1 The Noto 32-m Antenna: General Information and Current Status

The Noto 32-m antenna is a Cassegrain radio telescope operated since 1989, by the Istituto di Radioastronomia, now part of the INAF (Istituto Nazionale di AstroFisica).

The main feature of this instrument is an active surface, allowing continuous correction of gravitational deformation during observations.

At present the radio telescope operates in the frequency range 2.3–45 GHz.

The DBBC & FILA10G is operating for VLBI observations. As of the end of 2016, ESCS (Enhanced Single-dish Control System), a new antenna control system, has been installed to allow single dish observations and testing, calibration, and configurations of the receivers.

As of the end of 2015 a severely degraded subreflector has been replaced with a refurbished one. Also the mechanical part of the subreflector has been completely overhauled.

In 2016 the main structure of the elevator operating on the antenna has been replaced.

Istituto di Radioastronomia INAF, Noto

Noto Network Station

IVS 2015+2016 Biennial Report

2 Geodetic VLBI Observations

In 2015 and 2016 Noto has participated in nineteen routine geodetic 24-hour sessions: four IVS-T2, five IVS-CRF, eight EUROPE, and two VITA sessions.

Ny-Ålesund Geodetic Observatory

Moritz Sieber

Abstract In 2015–2016 the 20-m telescope at Ny-Ålesund, Svalbard, operated by the Norwegian Mapping Authority (NMA), took part in 241 out of 248 scheduled 24-hour and 97 one-hour sessions of the IVS program.

Fig. 1 Geodetic observatory, 20-m telescope, and the GFZ's satellite station.

1 General Information

The Geodetic Observatory of the Norwegian Mapping Authority (NMA) is situated at 78.9° N and 11.9° E in Ny-Ålesund, in Kings Bay, at the west side of the island Spitsbergen. This is the biggest island in the Svalbard archipelago. In 2015–2016, Ny-Ålesund was scheduled for 248 24-hour VLBI sessions, including R1, R4, EURO, RD, T2, and RDV sessions, and it participated in 97 one-hour sessions within the Intensives program. In addition to the 20-meter VLBI telescope, the Geodetic Observatory has two GNSS receivers in the IGS system and a Super Conducting Gravimeter in the Global Geodynamics Project (GGP) installed at the site. The French-German AWIPEV research base in Ny-Ålesund operates a DORIS station. In October 2004, a GISTM (GPS Ionospheric Scintillation and TEC Monitor) receiver was installed at the Mapping Authority's structure in the frame of ISACCO, an Italian research project on ionospheric scintillation observations, led by Giorgiana De Franceschi of the Italian Institute of Volcanology and Geophysics (INGV). Another Real-Time Ionospheric Scintillation (RTIS) monitor was set up by the NMA in November 2012.

Norwegian Mapping Authority, Geodetic Institute

NYALES20 Network Station

IVS 2015+2016 Biennial Report

2 Component Description

The antenna with a 20-m diameter is intended for geodetic use and receives in S- and X-band. Its design and construction are similar to those at Green Bank and Kokee Park. A rack with 14 video-converters, a Mark IV decoder, and a Mark 5 sampler streams the data to a Mark 5B+ recorder. Another Mark 5B+ unit is used to transfer data via network to the correlators. Alternatively, a DBBC2, (purchased in 2014) is connected in parallel to gradually replace the analog rack. Timing and frequency is provided by a NASA NR maser, which is monitored by a CNS system.

3 Staff

The staff at Ny-Ålesund consists of four people employed at 75%, which means that three full-time positions are covered (see Table 1 for an overview). Each position goes with a three-year contract that can be extended up to 12 years, but on average people stay three–four years. The observatory is part of the Geodetic Division of the Norwegian Mapping Authority with its main office in Hønefoss (near Oslo).

In April 2015, Geir returned from his sabbatical, and Axel Meldahl joined as a new engineer, after Anita and Alex returned back home. A year later, Kent did not extend his contract after three-and-a-half years. Moritz stepped down one level, and Stig Pedersen became the new station manager in August 2016.

Fig. 2 Changes in staff during 2015: Alex Burns and Anita Titmarsh (images: Bjørn-Owe Holmberg).

Table 1 Staff related to VLBI operations at Ny-Ålesund.

Hønefoss	Section Manager	Reidun Kittelsrud
	Assisting Section Manager	Frode Koppang
	Technical Manager	Leif Morten Tangen
Ny-Ålesund	Station Manager	Stig Pedersen (≥ Aug. '16)
	Station Manager	Moritz Sieber (≤ Aug. '16)
	Engineer	Alex Burns (≤ Mar. '15)
	Engineer	Geir Mathiassen (≥ Apr. '15)
	Engineer	Axel Meldahl (≥ Apr. '15)
	Engineer	Kent Roskifte (≤ Jul. '16)
	Engineer	Moritz Sieber (≥ Sep. '16)
	Engineer	Anita Titmarsh (≤ Apr. '15)

Fig. 3 Core team: Moritz Sieber, Axel Meldahl, and Geir Mathiassen.

Fig. 4 Changes in staff during 2016: Kent Roskifte and Stig Pedersen (image of Kent: Bjørn-Owe Holmberg).

4 Current Status and Activities

4.1 Maintenance

19 of the 34 sessions listed in Table 2 can be related to a telescope well up in its years. Some problems are easy to spot and expect, such as replacing worn-out signal cables in August 2015. Others are more subtle; the gearbox that was changed in 2013 never seems to be properly adjusted, and wear and tear resulted in loosening of some of the mounting bolts. Although they were being refitted on a daily basis, things got worse, resulting in broken bolts, torn-out threads, and finally the complete damage of the pinion with the loss of all

of its teeth. Luckily, the old gearbox got overhauled in the meantime, and things seem to have been done properly when it was mounted. Nevertheless, the maximum wind-speed for observations was reduced to lower the load on the structure.

One of the two RF-switches in our IF3-distributor got stuck in the "in"-state. Haystack had a spare and shipped it; in the meantime the advice from Rich to just toggle it a few times proved to be very successful.

The LO power supply for the receiver gradually drifted to higher voltages. Thanks to Brian we had a plan ready when it was finally unlocked in November. Most recently, a switch for the cable wrap sector broke and had to be replaced.

4.2 Monitoring

Good monitoring and routines will be an important part for the upcoming years, with parallel observations of old and new telescopes and no increase in staff.

The status page of data transfers (Figure 5) collects information from the current session's logfile (scan numbers and names) and the Master Schedule (correlator). A BASH script that wraps around Harro's "m5copy" (similar to tsunami autocontrol) both checks and claims bandwidth from the Bonn correlator's transfer page, toggles the status flag of the local information page, sends mails on starting, interruptions, and the end of the transfer, and checks if all data were transferred correctly.

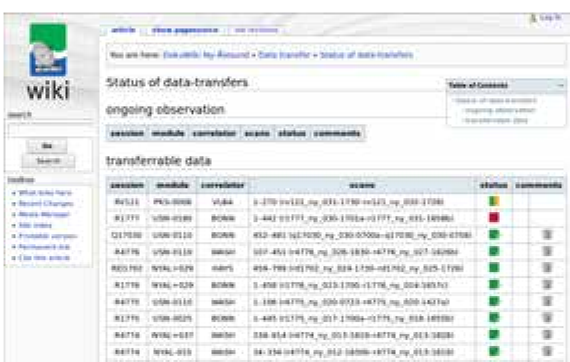

Fig. 5 Information page on transferable and transferred data.

4.3 Session Performance

Of the 248 scheduled 24-hour sessions during 2015 and 2016, Ny-Ålesund observed 241, as well as 97 one-hour Intensives. A broken Az gear was responsible for the non-observation of three sessions. Getting much more conservative with regard to wind speed limits, the threshold was lowered to $20\,\frac{\mathrm{m}}{\mathrm{s}}$; once the wind is higher, observations will be stopped. That caused R1766 not to be observed. During the following T2 session, the wind decreased, but the LO voltage had to be adjusted before any meaningful measurements could be done.

In 2015, the receiver dewar heated up just before R4698. It was decided to wait until it got cooled down again, which was after the session. The T2106 data was erased on site by mistake before it could be transferred to the correlator. A summary of all sessions with completion of 98% or less can be found in Table 2.

Table 2 Sessions with trouble (recorded 98% or less).

Session	Comments
R4718, R4720, R1765, R1766, T2114, R1768, R1772	stopped observation due to high windspeed ($> 20\,\frac{\mathrm{m}}{\mathrm{s}}$)
R4695, R4698, RD1605, R1759, R1764, EUR144	receiver dewar: taking measures to prevent further warming up and/or cooling down
R1697, R1699, R4744, R4764	power outage
R1747, RV118, R4747, R1748	stopped during unmanned hours (bolt of Az gear broken)
R1750, R4750, R1751, R4751	Az gear crashed
R1766, R2114	LO unlocked
R1672 RV120	loose sensor wires causing motor errors faulty cable wrap limit switch
R4735 T2106	lost at correlator, overwritten before retransmission erased module before data was transferred
R1686 R1713 R4749	DIMino not started faulty disk module Mark 5 trouble

4.4 New Observatory

In May 2015, the fiber cable to Longyearbyen, the former endpoint of high connectivity to the mainland, was established. Not necessarily part of the new observatory, it is a crucial requirement for its usability.

Due to limitations of the aviation authorities, the new telescopes could not be built close to the existing site (which is next to the airfield: the blue building in Figure 1 is the tower), but 2 km further out. Work on the station building lasted throughout 2015, and in 2016 the two MT Mechatronics 13.2-m telescopes were established.

Fig. 6 Main reflector installation on the north telescope of the new observatory.

The signal chain will have a tri-band feed to begin with; considering the state of the 20 m we do not want to wait too long to start parallel observations. DBBC3s and flexbuff are scheduled to arrive in early 2017.

Three pillars on the new site were equipped with GNSS receivers in late 2015; five more followed in 2016 after local movements in the terrain were detected.

4.5 New Instrumentation

The DBBC2 was gradually taken into operation, first alongside observations as a test, then, as the need arose due to a broken RF switch in the IF3 distributor, as a replacement for low X-band channels for EUR/RD/T2-sessions. After no further objections, Ny-Ålesund went fully DBBC in 2017.

Of all the toys for the new station, the T4Science iMaser 3000^{TM} arrived first. Since July 2016, it ticks happily away in its temperature-stabilized little room. A CNS system, analogous to the existing one, waits to be wired up.

5 Future Plans

2017–2018 will be the years of transition. The twin-telescopes will become operational, and one of the two will start parallel observations with the legacy system. Knowledge will have to be passed on, both from the project group to the operations staff and internally, because both Geir and Moritz will not extend their contracts. New routines will have to be established, and existing ones modified or further improved — it is not intended to increase the staff, and the 20-m system will not cease from demanding its (increasing) share of attention.

German Antarctic Receiving Station (GARS) O'Higgins

Alexander Neidhardt [1], Christian Plötz [2], Thomas Klügel [2], Torben Schüler [2]

Abstract After the update of the receiver front-end was finished in 2014, it was installed in O'Higgins in early 2015. The remote capabilities of the new receiver and the long service lifetimes of the dewar now allows the realization of VLBI sessions even when no BKG expert is on site. The integration of the VLBI schedules into the Satellite Monitor and Control Software (SMCS) of our partner DLR is currently in progress.

1 General Information

The German Antarctic Receiving Station (GARS) is jointly operated by the German Aerospace Center (DLR) and the Federal Agency for Cartography and Geodesy (BKG, belonging to the duties of the Geodetic Observatory Wettzell (GOW)). The Institute for Antarctic Research Chile (INACH) coordinates the logistics. The 9-m radio telescope at O'Higgins is mainly used for downloading of remote sensing data from satellites such as TanDEM-X and for the commanding and monitoring of spacecraft telemetry. DLR operating staff and a Chilean team for maintaining the infrastructure (e.g., power and freshwater generation, technical support) attend the station the entire year. During dedicated campaigns in the Antarctic summer it is also used for geodetic VLBI. BKG staff was on site from January to the end of February 2015 and from the beginning of February to early March 2016. During these two campaigns a total of seven 24-hour IVS sessions were recorded. In addition, the O'Higgins telescope participated in four 24-hour sessions by remote control.

Carriage of passengers and cargo by air and by ship was organized by the Chilean Antarctic Institute (INACH) in close collaboration with the Chilean Army, Navy and Airforce, and with the Brazilian and Uruguayan Airforce. All technical material and food for the entire stay are delivered from Punta Arenas via Base Frei on King George Island to O'Higgins on the Antarctic Peninsula. The conditions for landing on the glacier are strongly weather dependent and involve an increasing risk due to climate change; in general, transport of staff and cargo is always a challenging task. Arrival and departure times strongly depend on the climate conditions and on the logistic circumstances.

After each Antarctic winter the VLBI equipment at the station must be checked again. Damages resulting from the climate conditions or strong storms have to be identified and repaired. Shipment of each kind of material, such as special tools, spare parts, or upgrade kits, has to be carefully prepared in advance. The new hydrogen maser EFOS-50 is continuously running and doesn't need to be heated-up when the staff arrives. The maser status is permanently monitored remotely.

Besides the 9-m VLBI antenna, which is used for the dual purposes of receiving data from and sending commands to remote sensing satellites and performing geodetic VLBI, other geodetic-relevant instruments are also operated on site:

- currently two H-masers (EFOS-10 and EFOS-50), an atomic Cs-clock, a GPS time receiver, and a Total Accurate Clock (TAC) offer time and frequency.
- two GNSS receivers OHI2 and OHI3, operating in the frame of the IGS network, while both are

1. Forschungseinrichtung Satellitengeodäsie (FESG), Technische Universität München
2. Bundesamt für Kartographie und Geodäsie (BKG)

GARS O'Higgins Network Station

IVS 2015+2016 Biennial Report

Fig. 1 The Web cam image of the VLBI antenna from December 01, 2016.

Fig. 2 The daily companions of the O'Higgins team.

Galileo enabled. The receivers worked without failure.

- a meteorological station providing pressure, temperature, humidity, and wind information, as long as the temporarily extreme conditions did not disturb the sensors.
- a GPS referenced radar tide gauge being operated only during the Antarctic summer and a permanent recording underwater sea level gauge; operation ended in 2015.
- two SAR corner reflectors, which were installed in March 2013 as part of a network to evaluate the localization accuracy of the TerraSAR-X mission.

The geodetic reference points of the VLBI antenna and the GNSS antennas are surveyed on a more or less regular basis. The last local survey was done in February 2016 when also the reference points of the SAR corner cubes were precisely determined. The last absolute gravity measurement was done in 2012.

2 Staff

The members of staff for operation, maintenance, and upgrade of the VLBI system and other geodetic devices are summarized in Table 1.

Table 1 Staff members.

Name	Group	Function	Mainly working for
Torben Schüler	BKG	head of the GOW	GOW
Christian Plötz	BKG	electrical engineer (chief engineer RTW)	O'Higgins, RTW, TTW
Reiner Wojdziak	BKG	software engineer	O'Higgins, IVS Data Center Leipzig
Andreas Reinhold	BKG	geodesist	operator Leipzig, survey O'Higgins
Jan Müller	BKG	geodesist	operator Leipzig, survey O'Higgins
Theo Bachem	BKG	electrical engineer	SLR Wettzell, operator O'Higgins
Thomas Klügel	BKG	geologist	administration laser gyro/ local systems Wettzell
Swetlana Mähler	BKG	geodesist	survey, SLR Wettzell, logistics O'Higgins
Olaf Lang	BKG	electrical engineer	local systems/ SLR Wettzell, logistics O'Higgins
Alexander Neidhardt	FESG	head of the microwave group, VLBI chief	RTW, TTW
Gerhard Kronschnabl	BKG	electrical engineer (chief engineer TTW)	TTW, RTW

3 Observations in 2015—2016

GARS participated in the following sessions of the IVS observing program:

Antarctic summer campaign (January—February 2015):

- IVS-OHIG94 February 04-05, 2015
- IVS-OHIG95 February 10-11, 2015
- IVS-OHIG96 February 11-12, 2015
- IVS-T2102 February 17-18, 2015

Antarctic summer campaign (February—March 2016):

- IVS-OHIG100 February 09-10, 2016
- IVS-OHIG101 February 10-11, 2016
- IVS-OHIG102 February 17-18, 2016

Remotely operated sessions:

- IVS-T2106 October 06-07, 2015
- IVS-T2107 November 10-11, 2015
- IVS-OHIG99 November 18-19, 2015
- IVS-T2108 December 15-16, 2015

At O'Higgins, the recorded scans were copied locally to portable hard disks which were carried by the staff at their return to Wettzell. From there the data were transferred via Internet to the Bonn correlator.

4 Technical Improvements and Maintenance

Fig. 3 The new data acquisition rack with (from top) backup system, Field System PC, Mark 5B+ data recorder, and ADS3000+ gigabit sampler.

The VLBI receiver front-end, which was nearly completely re-built in 2014, was installed at the end of January 2015. After that, the complete VLBI data acquisition back-end was upgraded. This comprises the replacement of the analog baseband converters and the Mark IV formatter by an ADS3000+ Gigabit sampler and a Mark 5B+ recording system. A new Field System PC was also installed. All four following IVS sessions during this campaign were recorded on both the old and the new data acquisition systems to ensure that the new system was working properly.

The cooling system was maintained in February 2016 (compressor adsorber replacement, dewar heating, and evacuation).

The IT network was completely rearranged to prepare the system for a software controlled switching between satellite tracking and VLBI observation mode. The limited bandwidth of the satellite link of 2 MBit/s only allows low transfer rates on the communication line so that Internet transfer of VLBI data is not yet practicable.

Since the installation of the new maser EFOS-50 in February 2014, both masers have been running in parallel, where EFOS-50 is the primary one and EFOS-10 is in standby.

The radar tide gauge was temporarily installed in January 2015. Due to frequent failures of the system and the difficult to access site, it is no longer operated. The same applies to the underwater pressure gauge, which yielded no continuous time series due to failures and iceberg collisions.

The extreme environmental conditions in the Antarctic requires special attention to the GARS telescope and the infrastructure. Corrosion frequently results in problems with connectors and capacitors. Defective equipment needs to be detected and replaced. Special attention was given to the wind sensors, which are important for the operational safety of the antenna. Due to frequent corrosion of the ultrasonic sensor heads by salt and storm, classical wind anemometers recording up to 60 m/s wind speed were installed in addition. Also, the Web cams are regularly maintained.

5 Future Plans

A full integration of the VLBI schedules into the SMCS software of DLR is envisaged for the next months. Then a more regular participation in IVS observations should be feasible. For the next two years a substantial modernization of GARS O'Higgins is currently being prepared by DLR. The work will focus on the infrastructural facilities (2017—2018) and the 9-m antenna (2018—2019). Further ideas concern the use of Ka-band receiving systems.

Onsala Space Observatory – IVS Network Station Activities during 2015–2016

Rüdiger Haas, Thomas Hobiger, Gunnar Elgered, Niko Kareinen, Grzegorz Klopotek, Joakim Strandberg, Hans-Georg Scherneck

Abstract During 2015 and 2016 we participated in 98 IVS sessions. Additionally, we observed a small number of experimental sessions.

1 General Information

The Onsala Space Observatory is the national facility for radio astronomy in Sweden with the mission to support high-quality research in radio astronomy and geosciences. The geoscience instrumentation at Onsala includes equipment for geodetic VLBI, GNSS, a superconducting gravimeter with a platform for visiting absolute gravimeters, several microwave radiometers for atmospheric measurements, both GNSS-based and pressure-based tide gauges, and a seismometer. The Onsala Space Observatory can thus be regarded as a fundamental geodetic station.

In January 2015, the Onsala Twin Telescopes (OTT) project officially started with infrastructure work, i.e., building concrete towers for the telescopes, concrete installation platforms, road work, and a computer and fiber network. The OTT telescopes were delivered in June 2016 and the assembly and installation continued until the end of November.

The staff members associated with the IVS Network Station at Onsala are listed in Table 1.

Chalmers University of Technology, Department of Earth and Space Sciences, Onsala Space Observatory

Onsala IVS Network Station

IVS 2015+2016 Biennial Report

2 Geodetic VLBI Observations

In total, we participated in 45 and 53 IVS sessions during 2015 and 2016, respectively (see Table 2).

All sessions were recorded with the DBBC/Mark 5B+ system. The sessions to be correlated at the Bonn correlator were recorded in parallel in mk5b-format on the FlexBuff. These data were then e-transferred to Bonn for correlation. For a few sessions the Flexbuff-recording failed and thus the data recorded on Mark 5B-modules were read out and e-transferred to the correlator.

In 2015, two sessions suffered from a wrong setup and a power failure, respectively, causing data loss for several hours. Also in 2016, one session was affected by a technical problem that caused several hours of data loss, and we lost one complete session due to communication and planning mistakes.

In addition to the IVS sessions, we observed a few test experiments together with Wettzell, for atmospheric studies and to observe the APOD satellite.

3 Monitoring Activities

We continued with the monitoring activities as described in previous annual reports:

Local tie vector at Onsala.

In the autumn of 2015, we performed an experimental campaign together with Metsähovi to simultaneously monitor the telescope reference points with automated monitoring systems during ongoing VLBI experiments and to perform local tie measurements using classical measurements and GNSS.

Table 1 Staff members associated with the IVS Network Station at Onsala. All e-mail addresses have the ending @chalmers.se, and the complete telephone numbers start with the prefix +46-31-772.

Function	Name	e-mail	telephone
Responsible P.I.s for geodetic VLBI observations	Rüdiger Haas	rudiger.haas	5530
	Thomas Hobiger	thomas.hobiger	5549
Observatory director	John Conway	john.conway	5503
Head of department	Gunnar Elgered	gunnar.elgered	5565
Ph.D. students involved in geodetic VLBI	Niko Kareinen	niko.kareinen	5566
	Grzegorz Klopotek (2015.04.01–)	grzegorz.klopotek	5575
	Joakim Strandberg (2015.10.10–)	joakim.strandberg	5566
Responsible for the VLBI Field System	Michael Lindqvist	michael.lindqvist	5508
	Rüdiger Haas	rudiger.haas	5530
Responsible for the VLBI equipment	Karl-Åke Johansson	karl-ake.johansson	5571
	Leif Helldner	leif.helldner	5576
Responsible for the VLBI operators	Roger Hammargren	roger.hammargren	5551
Telescope scientist	Henrik Olofsson	henrik.olofsson	5564
Software engineer	Mikael Lerner	mikael.lerner	5581
Responsible for gravimetry	Hans-Georg Scherneck	hans-georg.scherneck	5556

The data analysis is still ongoing and a corresponding publication is in preparation.

Vertical height changes of the telescope tower.

We continued to monitor the vertical height changes of the telescope tower using the invar rod system at the 20-m telescope. The measurements are available at `http://wx.oso.chalmers.se/pisa/`.

Calibration of pressure sensor.

We continued to calibrate the Onsala pressure sensor using a transportable Vaisala barometer borrowed from the Swedish Meteorological and Hydrological Institute (SMHI). This latter instrument was installed at Onsala in late 2002. It has since then been calibrated regularly at the SMHI main facility in Norrköping with traceability to SI. The last calibration occurred on September 29, 2015. At this occasion, the largest deviation was 0.05 hPa over the input range from 800 hPa to 1100 hPa. The VLBI pressure sensor that had failed in late December 2014 was replaced by an identical one in February 2015. In the mean time a spare sensor mounted at a different height was used. The new sensor appears, however, to have a small offset compared to the one that failed in 2014 (see Figure 1).

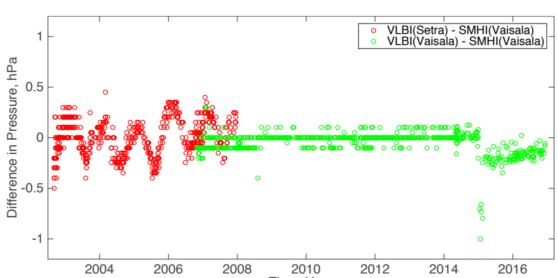

Fig. 1 Time series of pressure differences between the VLBI pressure sensors and the calibrated pressure sensor from SMHI.

Microwave radiometry.

The older water vapor radiometer (WVR), Astrid, was operating continuously from May to the end of December 2015 but with a data gap from mid-August to mid-September. During 2016, Astrid was operating from mid-February to the end of June and from early August to mid-December. During the first of these two periods the temperature regulation failed but the data may still be useful. The Konrad WVR was operating from February to end of June 2015. It started to operate again in May 2016 until the end of the year.

The data analysis for both WVRs is not completed and therefore a final check of the data quality has not occurred yet.

Table 2 Geodetic VLBI observations at Onsala during 2015 and 2016. The third and sixth column gives some general remarks and information on the percentage of the scheduled Onsala (On) observations that were used in the analysis (as reported on the Web pages for the IVS session analyses), compared to the station average (StAv) percentage per experiment.

Exp.	Date	Remarks	Exp.	Date	Remarks
EUR.133	15.01.19	OK	R1.723	16.01.18	OK: 93.7 % (StAv 90.3)
R1.671	15.01.20	OK: 86.4 % (StAv 67.1 %)	RV.115	16.01.19	OK: 88.2 % (StAv 75.6)
RV.109	15.01.28	OK: 78.7 % (StAv 59.8 %)	RD.16.01	16.01.20	not correlated yet
R1.673	15.02.02	OK: 80.5 % (StAv 63.0 %)	EUR.139	16.01.25	OK
RD.15.01	15.02.03	OK: 84.4 % (StAv 71.9 %)	R1.724	16.01.26	OK: 90.3 % (StAv 77.9)
R1.675	15.02.16	OK: 92.8 % (StAv 78.6 %)	R1.726	16.02.08	OK: 85.4 % (StAv 67.7)
T2.102	15.02.17	OK	RV.116	16.02.09	OK: 87.0 % (StAv 77.4)
R1.681	15.03.30	OK: 75.4 % (StAv 61.3 %)	R1.727	16.02.15	OK: 84.2 % (StAv 71.9)
R1.682	15.04.07	OK: 68.3 % (StAv 56.5 %)	T2.109	16.02.16	OK
RD.15.02	15.04.08	OK: 87.2 % (StAv 75.0 %)	R1.732	16.03.21	OK: 90.8 % (StAv 75.2)
R1.684	15.04.20	OK: 93.1 % (StAv 87.8 %)	EUR.140	16.03.22	OK
T2.103	15.04.21	not correlated yet	R1.733	16.03.29	OK: 85.3 % (StAv 83.0)
RV.111	15.04.22	OK: 93.3 % (StAv 80.4 %)	R1.734	16.04.04	OK: 80.0 % (StAv 59.3)
R1.685	15.04.27	OK: 89.0 % (StAv 86.0 %)	T2.110	16.04.05	OK
R1.686	15.05.04	OK: 91.7 % (StAv 85.2 %)	EUR.141	16.04.06	OK
EUR.135	15.05.05	OK	R1.736	16.04.18	OK: 85.5 % (StAv 71.4)
RD.15.03	15.05.06	OK: 84.9 % (StAv 63.3 %)	RV.117	16.04.19	OK: 93.5 % (StAv 93.1)
R1.689	15.05.26	23.1 % (StAv 61.0 %) (16 h wrong setup)	RD.16.03	16.04.20	OK: 81.3 % (StAv 71.3)
R1.694	15.06.29	OK: 90.4 % (StAv 78.6 %)	R1.737	16.04.26	OK: 82.7 % (StAv 61.1)
T2.104	15.06.30	OK	R1.740	16.05.17	OK: 85.9 % (StAv 75.0)
R1.695	15.07.06	OK: 54.6 % (StAv 52.1 %	RD.16.04	16.05.18	not correlated yet
RD.15.05	15.07.07	not correlated yet	R1.746	16.06.27	OK: 89.6 % (StAv 85.3)
RD.15.06	15.07.29	not correlated yet	RD.16.05	16.06.28	OK: 84.7 % (StAv 78.9)
R1.700	15.08.11	OK: 88.6 % (StAv 86.9 %)	R1.747	16.07.04	OK: 79.8 % (StAv 69.4)
R1.701	15.08.17	OK: 80.3 % (StAv 56.8 %)	RV.118	16.07.06	OK: 86.4 % (StAv 76.7)
R1.702	15.08.24	OK: 68.3 % (StAv 57.7 %)	R1.748	16.07.11	OK: 83.5 % (StAv 81.7)
T2.105	15.08.25	OK	R1.749	16.07.18	OK: 86.3 % (StAv 84.9)
RD.15.07	15.08.26	not correlated yet	R1.750	16.07.25	OK: 89.9 % (StAv 81.3)
R1.703	15.08.31	OK: 89.1 % (StAv 72.7 %	R1.754	16.08.22	OK: 94.5 % (StAv 91.6)
EUR.137	15.09.07	OK	T2.112	16.08.23	OK
R1.704	15.09.08	OK: 79.6 % (StAv 65.2 %)	RD.16.07	16.08.24	OK: 85.1 % (StAv 78.1)
RV.113	15.09.09	OK: 90.3 % (StAv 76.9 %)	R1.755	16.08.29	OK: 77.6 % (StAv 60.7)
R1.706	15.09.21	55.1 % (StAv 67.1) (8 h power failure)	EUR.143	16.09.05	OK: but 45 min lost
R1.709	15.10.13	OK: 77.3 % (StAv 64.1 %)	R1.756	16.09.06	OK: 81.1 % (StAv 68.2)
R1.713	15.11.09	OK: 74.7 % (StAv 61.4 %)	RD.16.08	16.09.07	49.8 % (StAv 59.4) (11 h lost)
T2.107	15.11.10	OK	R1.757	16.09.12	OK: 88.8 % (StAv 65.4)
R1.715	15.11.23	OK: 86.2 % (StAv 68.3 %)	RD.16.09	16.09.13	not correlated yet
RD.15.09	15.11.25	OK: 80.6 % (StAv 61.7 %)	RV.119	16.09.14	OK: 90.3 % (StAv 84.8)
RD.15.10	15.12.01	not correlated yet	R1.758	16.09.19	OK: 88.6 % (StAv 82.8)
R1.717	15.12.07	OK: 93.9 % (StAv 81.4 %)	R1.759	16.09.26	OK: 76.4 % (StAv 59.0)
R1.718	15.12.14	OK: 91.2 % (StAv 82.0 %)	R1.760	16.10.04	OK: 62.0 % (StAv 39.7)
T2.108	15.12.15	OK	RD.16.10	16.10.05	OK: 82.1 % (StAv 58.7)
EUR.138	15.12.16	OK	T2.113	16.10.18	OK
R1.719	15.12.21	OK: 92.6 % (StAv 88.2 %)	R1.767	16.11.21	OK: 75.7 % (StAv 45.8)
R1.720	15.12.28	OK: 90.0 % (StAv 82.6 %)	EUR.144	16.11.24	OK
			R1.768	16.11.28	OK: 63.6 % (StAv 44.7)
			RD.16.11	16.11.29	not correlated yet
			RV.120	16.11.30	OK: 91.0 % (StAv 86.7)
			T2.215	16.12.06	lost
			R1.770	16.12.12	OK: 86.4 % (StAv 66.5)
			RD.16.12	16.12.13	not correlated yet
			RD.16.13	16.12.19	not correlated yet
			R1.771	16.12.20	OK: 93.3 % (StAv 91.0)

Sea-level monitoring.

The GNSS-R based tide gauge was operated continuously and data were analyzed [1, 2]. The new (traditional) tide gauge station with a radar sensor and pressure sensors, inside and outside the well, was inaugurated officially in September 2015. It is now part of the national tide gauge monitoring network of the Swedish Meteorological and Hydrological Institute (SMHI).

Fig. 2 The Onsala super tide gauge inaugurated in September 2015 and since then operated together with SMHI.

Superconducting gravimetry.

The superconducting gravimeter operated continuously and produced a highly precise record of gravity variations. No data were lost in 2015 and 2016. Tide solutions were prepared on a weekly basis and results are available on the SCG homepage (http://holt.oso.chalmers.se/hgs/SCG/toe/toe.html).

Absolute gravimetry.

In 2015, we supported a visiting absolute gravity measurement campaign with two gravimeters operating in parallel, a novel quantum gravimeter from the Humboldt University in Berlin, Germany, and a traditional FG5 instrument from Leibniz University, Hannover, Germany [3]. In 2016 we had another visit from Lantmäteriet, the Swedish mapping, cadastral, and land registration authority, with a traditional FG5 instrument.

Seismological observations.

The seismometer owned by Uppsala University and the Swedish National Seismic Network (SNSN) was operated throughout the two-year period.

4 Future Plans

- In the coming two years we plan to participate in about 50 IVS sessions per year with the 20-m telescope. We aim at becoming a "VDIF-only" station, i.e., to record data exclusively in VDIF-format.
- The Onsala Twin Telescopes (OTT), see Figure 3, will be commissioned during 2017. The official inauguration is planned for 18 May 2017. The goal is to start as soon as possible in 2017 to participate in VGOS test sessions and to be part of the CONT17 campaign with the OTT. For 2018 we expect to ramp up the VGOS observations considerably.
- A new GNSS reference station will be built in 2017 in the vicinity to the OTT. Also monuments for local tie measurements and telescope reference point monitoring will be established in 2017.
- In the summer of 2017 we will start tests with a newly developed microwave radiometer. In the long run it is likely to be located close to the OTT.
- The monitoring activities reported above will be continued.

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Fig. 3 The Onsala telescope cluster in 2016 with the new Onsala Twin Telescopes in the center of the photo. The new VGOS radio telescopes are equipped with reflectors of 13.2-m diameter. The radio telescope on the left hand side is the 25.6-m telescope installed in 1964, which is the first European telescope ever to be involved in VLBI. First geodetic VLBI measurements were performed already in 1968. The white radome on the right side of the picture houses the 20-m radio telescope installed in 1976, which was used with the Mark III geodetic VLBI system since 1979 and has the longest time series in the International VLBI Service for Geodesy and Astrometry (IVS) database. Close to the radome, but not visible in the photo, is the GNSS station ONSA, which was established already 1987 in the CIGNET network, several years before the International GNSS Service (IGS) was founded. ONSA had a pioneering role in the early days of GNSS, and has the longest continuous time series in the IGS network. There is also a gravimeter laboratory with a superconducting gravimeter. Shown in the picture foreground is the Onsala super tide gauge inaugurated in 2015. The observatory is one of the unique fundamental space geodetic sites that have a direct access to the sea level and co-locate VLBI, GNSS, gravimetry, and sea level monitoring. It is thus an important co-location site for the Global Geodetic Observing System (GGOS).

Parkes Network Station Report 2015–2016

John Reynolds

Abstract This report discusses observing done by the Parkes 64-m telescope during 2015 and 2016 and the future outlook for the telescope.

1 Observing in 2015 and 2016

The Parkes 64-m telescope participated in 11 24-hour IVS sessions over the 2015–2016 period, after a hiatus in 2014.

Nine of these sessions were made as part of the AUSTRAL VLBI observing program, linking the Australian AuScope VLBI antennas at Hobart, Katherine, and Yarragadee, as well as the antennas at Warkworth (New Zealand) and Hartebeesthoek (South Africa). The other two sessions were conducted as part of an observing program established by the Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV), targeting a number of new candidate astrometric sources including several radio stars and adjacent phase-reference sources.

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IVS 2015+2016 Biennial Report

Parkes also participated in two 24-hour sessions as part of a program led by Leonid Petrov (ADNET systems/GSFC) of hybrid astronomy/geodesy observations, refining the locations of several southern hemisphere radio stations that are equipped with neither dual S/X receiving systems nor IVS-compatible recording systems. This program also aims to identify additional calibrator sources in the Southern Hemisphere for “densification” of the ICRF in the South.

2 Outlook

While the operational funding outlook for a continuing role in astrometric and geodetic VLBI programs remains uncertain, all avenues to sustain the current levels of participation of Parkes are being actively pursued.

Shanghai Station Report for 2015–2016

Bo Xia, Xiaoyu Hong, Zhiqiang Shen, Qinghui Liu

Abstract This report summarizes the observing activities at the Sheshan station (SESHAN25) and the Tianma station (TIANMA65) in 2015 and 2016. It includes the international VLBI observations for astrometry, geodesy, and astrophysics and domestic observations for satellite tracking. We also report on updates and development of the facilities at the two stations.

1 General Information

The Sheshan station ('SESHAN25') is located at Sheshan, 30 km west of Shanghai. It is hosted by Shanghai Astronomical Observatory (SHAO), at the Chinese Academy of Sciences (CAS). The 25-meter radio telescope is in operation at 3.6/13, 5, 6, and 18 cm wavelengths. The Sheshan VLBI station is a member of the IVS and EVN. The Tianma station ('TIANMA65') is located in the western suburbs of Shanghai, Sheshan town, Songjiang district. It is jointly funded by the Chinese Academy of Sciences (CAS), Shanghai Municipality, and the Chinese Lunar Exploration Program. The telescope construction started in early 2009, and the majority of the mechanical system was completed in October 2012. On December 2, 2013, the Tianma 65 telescope passed its acceptance evaluation. By design, the Tianma telescope with a diameter of 65 meters, one of the largest steerable radio telescopes in the world, is a multifunction facility, conducting astrophysics, geodesy, and astrometry, as well as space science. By the end of 2016, Tianma 65 was equipped with seven cryogenic receiver systems (L, C, S/X, Ku, X/Ka, K, and Q). A CDAS and a DBBC2 were installed at the Tianma 65-m telescope for VLBI data acquisition. SESHAN25 and TIANMA65 take part in international VLBI experiments for astrometry, geodesy, and astrophysics research. Apart from its international VLBI activities, the telescope spent a large amount of time on China's Lunar Exploration Project and single dish observations for pulsar and spectral line research.

Shanghai Astronomical Observatory

SHAO Network Station

IVS 2015+2016 Biennial Report

2 Component Description

In 2015, the SESHAN25 telescope participated in 28 IVS sessions (including ten INT3 Intensive sessions). And TIANMA65 participated in five IVS sessions. In 2016, the SESHAN25 telescope participated in 36 IVS sessions (including ten INT3 Intensive sessions). And TIANMA65 participated in four IVS sessions.

Table 1 Statistics of experiments observed.

Session Name	2015 (SH)	2016 (SH)	2015 (T6)	2016 (T6)
AOV	2	3	1	1
APSG	1	2	0	0
AUS-AST	0	1	0	1
IVS-R1	10	15	0	0
IVS-T2	1	2	0	0
IVS-R&D	4	3	2	2
IVS-CRF	0	0	2	0
IVS-INT3	10	10	0	0

3 Current Status and Activities

3.1 Antenna Maintenance with SESHAN25

From November 26, 2015 to February 13, 2016, the rail and the gear box were replaced. We also did some maintenance work with antenna winding and others. From November to December 2016, we did some maintenance work with antenna structure reinforcement and spray paint, etc.

Fig. 1 Antenna maintenance of the SHESHAN 25-m telescope.

3.2 Antenna Maintenance with TIANMA65

From March 19 to April 26, 2015, the elevation drive structure installation and commissioning was done. From April 28 to May 23, 2016, we also did some antenna maintenance such as painting at a rusted place, replacing a nylon wheel guide rail coat, screwing in primary panel bolts, replacing winding at a central pivot, maintaining and testing azimuth and elevation code, and replacing actuators of the active surface. The accuracy of the primary reflector surface reached 0.3 mm after the primary panel bolts were screwed in. The elevation speed motor was replaced during June 2016.

3.3 Other Upgrades

We installed a new DBBC2 at SESHAN25 in December 2015 and began to use it in March 2016. For the DBBC2 at Tianma65, strong RFI was found in the bandpass when using V105-E mode, so we plan to have it repaired.

3.4 Seshan VGOS Station Construction

The Sheshan VGOS station is located at the yard of the Tianma radio telescope. Now the foundation's underground part is being built, the receiver with a frequency range from 2.7 GHz to 18 GHz is being manufactured, the data acquisition equipment CDAS-2A is ready with the capability of 8 x 512 Gbps/s, the antenna is ready to be installed, and two Mark 6 recorders have also been purchased. The hydrogen clock and the meteorological system will be shared with TIANMA65. The station integration is scheduled for this August. The station is expected to do test observations at the end of this year.

4 The Staff of the Shanghai VLBI Station

Table 2 lists the group members at the Shanghai VLBI Station. The staff is involved in the VLBI program at the station with various responsibilities.

5 Future Plans

In 2017, SESHAN25 will take part in 30 IVS sessions and 13 INT3 sessions. Meanwhile, TIANMA65 will take part in five IVS sessions. The telescopes are also scheduled to track China's lunar probe in the Chang'e-5 sample return mission.

Fig. 2 Antenna maintenance of the Tianma 65-m telescope.

Table 2 The staff at the Shanghai VLBI station.

Name	Background	Position and Duty	Contact
Xiaoyu Hong	Astrophysics	Director, Astrophysics	xhong@shao.ac.cn
Zhiqiang Shen	Astrophysics	Deputy Director	zshen@shao.ac.cn
Qinghui Liu	Radio technique	Chief Engineer	liuqh@shao.ac.cn
Qingyuan Fan	Ant. Control	Professor, Antenna	qyfan@shao.ac.cn
Bin Li	Microwave	Technical friend, Receiver	bing@shao.ac.cn
Bo Xia	Electronics	VLBI friend, Director of Ope.	bxia@shao.ac.cn
Jinqing Wang	Electronics	Engineer, Antenna	jqwang@shao.ac.cn
Lingling Wang	Software	Engineer, Timing system	llwang@shao.ac.cn
Rongbing Zhao	Software	Engineer, Antenna software	zhaorb@shao.ac.cn
Li Fu	Ant. Mechanical	Engineer, Antenna	fuli@shao.ac.cn
Jian Dong	Software	Engineer, Antenna	dongjian@shao.ac.cn
Weiye Zhong	Microwave	Engineer, Receiver	wyzhong@shao.ac.cn
Wei Gou	Electronics	Operator, Engineer	gouwei@shao.ac.cn
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Yongbin Jiang	Electronics	Operator, Engineer	jyb@shao.ac.cn
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Yongchen Jiang	Electronics	Operator, Disk shipping	yongchen@shao.ac.cn
Ying Chen	Microwave	Operator, Engineer	cying@shao.ac.cn

The Helio-Geodynamic Testing Ground Area "Simeiz–Katsiveli": Some Results of the Observation Analysis

A.E. Volvach, G.S. Kurbasova, L.N. Volvach

Abstract We summarize briefly the status of our 22-m radio telescope as an IVS Network Station. Solving the problem of forecasting catastrophic natural and manmade phenomena in the Crimean peninsula it is connected with the organization of the complex network of local observations of helio-geodynamic testing areas. We show some results of this polygon "Simeiz–Katsiveli". The aim is to show that the polygon operates as an international Center of Earth data parameters.

1 General Information

In 1994, RT-22 expanded its international cooperation in the field of very long baseline radio interferometry in geodetic programs (Figure 1). NASA, MAO NASU, IPA RAS, and SRI RAS created a new generation VLBI station—the Simeiz VLBI station. Based on RT-22 and stations of space geodesy and geodynamics, the geodynamic "Simeiz–Katsiveli" area was created, which includes three complementary observing technologies (VLBI, SLR, and GNSS).

The Simeiz geodynamics area consists of the radio telescope RT-22, two satellite laser ranging stations, a permanent GPS receiver, and a tide gauge.

Parameters of the 22-meter radio telescope are presented in Table 1.

Radio Astronomy and Geodynamics Department of Crimean Astrophysical Observatory

Crimean Network Station

IVS 2015+2016 Biennial Report

2 Activities during the Past Two Years and Current Status

During the last two years the Space Geodesy and Geodynamics stations regularly participated in the international network programs of the IVS, the International GNSS Service (IGS), and the International Laser Ranging Service (ILRS).

During the period 1 January 2015 through 31 December 2016, the Simeiz VLBI station participated in seventeen 24-hour geodetic sessions. Simeiz regularly participated in the EUROPE and T2 series of the geodetic VLBI sessions.

Effects of Global Geodynamic Processes on Climate Characteristics of Crimea

In recent decades, geodynamics has become an area of intensive international scientific research, including plate tectonics on global and regional scales, i.e., studies of the movements of the earth's crust as well as the study of the rotation of the Earth and other phenomena, such as tides. In addition, research was done to deepen our knowledge of the gravitational and magnetic fields of the Earth. A common requirement for these studies is the need to create an accurately defined reference system (or systems), with respect to which all observations could be conducted and within which it is possible to formulate theories and models of the dynamics of the Earth. With regard to measurements on the surface, all modern methods (VLBI, SLR, and GNSS) determine the parameters of the Earth's rotation relative to three different coordinate systems. These co-

Fig. 1 Simeiz VLBI station.

Table 1 The antenna parameters of the Simeiz VLBI station.

Diameter D	22 m
Surface tolerance (root mean square)	0.25 mm
Wavelength limit	2 mm
Feed System	Cassegrain system or primary focus
Focal length F	9.525 m
Focal ratio F/D	0.43
Effective focal length for Cassegrain system	134.5 m
Mount type	Azimuth-Elevation
Pointing accuracy	10 arcseconds
Maximum rotation rate	1.5 degrees/second
Maximum tracking rate	150 arcseconds/second
Working range in Azimuth (0 to South)	-270 ± 270 degrees
in Elevation	0 – 85 degrees

ordinate systems are differently sensitive to different parameters. Therefore, in order to separate the various effects in the rotation of the Earth, all three measurement methods must be supported. Improvement of the technical level of the equipment will ensure the contribution of these methods to the solution of geodynamical problems from the point of view of three levels of accuracy: decimeter, centimeter, and millimeter.

As shown by our analysis of satellite data, the connection of local climatic and geophysical characteristics with the rotation of the Earth is beyond doubt. However, its impact on the economically important points of the Crimean peninsula (e.g., due to the diversity of the terrain, man-made conditions) should be monitored by regular terrestrial and space observations. Against the background of stable oscillations, abrupt changes and deviations from the stationary state can serve as a signal for environmentally unfavorable events. In our work [1] it was shown that the moment of occurrence of these events and localization in space can be detected by means of wavelet analysis. The results obtained by us stimulate the further development of the idea of creating a single helio-geodynamic system of the Crimean peninsula in the general system of observations of the planet Earth.

Solving the problem of forecasting catastrophic natural and man-made phenomena in the Crimea it is connected with the organization of complex observations in a network of local geodynamic polygons. In the spectrum of the time-frequency wavelet analysis of satellite data on an insolation incident on the Earth's surface at the point of the Kara-Dag in the period from 1983.5 to 2005.5, geodynamic effects of regular oscillations and, since 1999, an oscillation of unknown nature were found.

An accelerated increase of the surface temperature of the earth was detected in "Nikitsky Botanical Garden" after 1988. Based on the analysis of ground measurements of temperature in the air at 2 m height and at the earth's surface for the period from 1930 to 2014, we discuss possible causes of the acceleration.

The International Terrestrial Reference Frame (ITRF) is a set of points with their three-dimensional Cartesian coordinates which realize an ideal reference system. However, in the face of increasing opportunities for observation, as well as taking into account social and scientific goals, it is necessary to support spatio-temporal reference systems for monitoring global changes and for accurate navigation in space that must correspond to the required level of accuracy, guaranteeing a solid basis for measuring the effects of global changes and for high-precision navigation near the Earth and in deep space. The contribution of various scientific organizations that study problems in geodetic, astronomical, and space sciences allows the organization of complex interdisciplinary support of reference systems. This coordinated approach allows for a deeper understanding of the Earth as an integrated system.

The quasi inertial reference frame DTRF, determined by the DGFI (Deutsches Geodätisches Forschungsinstitut), includes corrections to deformations of the Earth, computed using homogeneous geophysical models for the "Ocean", "Atmosphere", and "Hydrology." An analysis of the three time series of corrections to the Earth deformations of the Simeiz station, calculated by the Atmosphere model for the period 1980–2014, revealed a significant fluctuation with a period of 1 year in the eastern and vertical components of the sea. The parameters of this oscillation for each component of the corrections are stable to a change in the order of n of the sinusoidal model. In addition to the annual wave, the model for n = 2 and n = 3 contains oscillations with periods of about 370, 353, and 182 days.

In the northern component, there are no continuous periodic oscillations in the frequency interval under consideration.

As a result, we can assume that the generation of periodic oscillations in the frequency range under consideration is related to the dynamics of the motion of the Moon and the Earth around the Sun.

3 Future Plans

Our plans for the coming years are to

- put into operation the VLBI Data Acquisition System DBBC,
- upgrade the laser of SLR Simeiz-1873 station, and
- set up a new GPS station near Simeiz VLBI station.

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Svetloe Radio Astronomical Observatory 2015–2016 Report

Sergey Smolentsev, Ismail Rahimov, Dmitry Ivanov

Abstract The current status as well as activities in 2015 and 2016 of the Svetloe Radio Astronomical Observatory are considered.

1 General Information

The "Quasar" VLBI Network is a unique Russian astronomical instrument created in the Institute of Applied Astronomy of the Russian Academy of Sciences (IAA RAS). The Network consists of three observatories including Svetloe in the Leningrad Region, Badary in Eastern Siberia, and Zelenchukskaya in the Northern Caucasus, and the Data Processing Center in St. Petersburg. Svetloe Observatory (Figure 1) was the first to be put into operation in 1999, the next was Zelenchukskaya in 2002, and finally Badary in 2005. Each observatory is equipped with at least three co-located instruments of different techniques: VLBI, SLR, combined GNSS receivers, and the DORIS system (Badary Observatory) [1]. The main instrument in each of three observatories is a 32-m radio telescope (RT-32), which provides a completely automatic process of observing radio sources and satellites in a radiometric or a radio interferometric mode. The main technical characteristics of the antennas are presented in Table 1. The RT-32 radio telescopes equipped with highly sensitive receivers provide signal amplification in 1.35 cm, 3.5 cm, 6 cm, 13 cm, and from 18 cm to 21 cm frequency bands in both circular polarizations. The baselines of the radio interferometer vary from 2,000 to 4,400 km. All observatories are linked by optical fiber lines and are equipped with identical hydrogen Time Standards, Water Vapor Radiometers, and meteorological stations, which are used by all types of observations.

Institute of Applied Astronomy of RAS

Svetloe Network Station

IVS 2015+2016 Biennial Report

Fig. 1 Svetloe Observatory.

2 Activities during the Past Two Years

Upgrading of the "Quasar" VLBI Network started in 2012. The aim of the upgrade was to create a Radio Interferometer of the new generation for improving the accuracy, reliability, and efficiency of providing the Earth rotation parameters to consumers in Russia and abroad. The Radio Interferometer of the new generation is designed to operate as part of the "Quasar" and international VLBI Networks. Currently, this new Radio Interferometer operates successfully and consists of two multi-band fast rotating Antenna Systems with

Table 1 Specifications of RT-32.

Mount	alt-azimuth
Configuration	Cassegrain
Subreflector scheme	asymmetrical
Main mirror diameter	32 m
Subreflector diameter	4 m
Focal length	11.4 m
Azimuth speed	1.0 °/sec
Elevation speed	0.5 °/sec
Limits by Az	$\pm 265°$
Limits by El	$0° - 85°$
Axis offset	-6.7 ± 1.0 mm
Tracking accuracy	± 10 arcsec
Surface accuracy (RMS)	0.5 mm
Frequency range	1.4 – 22 GHz
Polarization	LCP + RCP

a mirror diameter of 13.2-m (RT-13), which were installed at the Zelenchukskaya and Badary observatories in 2015 [2]. Installation works at Svetloe Observatory are scheduled to be completed in 2018.

During 2015–2016, RT-32 at Svetloe Observatory participated in both IVS and domestic (Ru-E and Ru-I) VLBI observations. Activities of the observatory are presented in Table 2. e-VLBI data transfer is used in the Svetloe for the domestic Ru-I sessions.

Table 2 VLBI observations of RT-32 of Svetloe Observatory.

Sessions	2015	2016
IVS-R4	23	18
IVS-T2	1	5
EUROPE	2	5
IVS-Intensive	19	18
Ru-E	37	35
Ru-I	16	4

3 Future Plans

In the next two years, the Svetloe Observatory will continue to participate in IVS and domestic VLBI observations, upgrade of the existing equipment, and replacement of obsolete equipment.

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Tsukuba 32-m VLBI Station

Masayoshi Ishimoto [1], Michiko Umei [1], Tomoo Toyoda [1], Takahiro Wakasugi [1], Ryoji Kawabata [1], Basara Miyahara [1], Katsumi Numajiri [1,2], Masatoshi Nakagawa [1,2]

Abstract The Tsukuba 32-m VLBI station was operated by the Geospatial Information Authority of Japan from 1998, and it stopped its operations at the end of 2016. This report summarizes activities of the Tsukuba 32-m VLBI station and the Ishioka Geodetic Observing Station, which is a successor to the Tsukuba 32-m VLBI station and fully compliant with the VGOS concept, in 2015 and 2016. Tsukuba 32 m participated in 139 24-hour sessions and 368 Intensive sessions, and Ishioka participated in 61 24-hour sessions and 31 Intensive sessions in accordance with the IVS Master Schedules of 2015 and 2016. In addition to these legacy sessions, Ishioka carried out collaborative broadband observations with several IVS stations, and we confirmed the compatibility of equipment between Ishioka and the other stations.

1 General Information

The Tsukuba 32-m VLBI station (Figure 1, hereafter Tsukuba 32 m) is located at the Geospatial Information Authority of Japan (hereafter GSI) headquarters in Tsukuba science city, which is about 50 km to the northeast of Tokyo. Ishioka Geodetic Observing Station (Figure 2, hereafter Ishioka) is located about 17 km to the northeast of the Tsukuba 32 m. In addition to these stations, GSI had operated two regional stations, Chichijima and Aira (Figure 3) and terminated their operations in March 2015, because these stations were originally established for maintaining the geodetic reference frame of Japan and the role had been replaced by GNSS continuously operating reference stations. Therefore, domestic VLBI sessions, JADE (JApanese Dynamic Earth observation by VLBI) which had been carried out by GSI since 1996 in order to maintain the reference frame of Japan and to monitor plate motions, were also terminated in 2015.

In 2015 and 2016, Tsukuba 32 m participated in international sessions as in the past. Ishioka also started to participate in legacy S/X sessions with Tsukuba 32 m in order to determine the accurate relative position between Tsukuba 32 m and Ishioka. In addition to these legacy sessions, Ishioka observed several broadband sessions compatible with the VGOS frequency setup.

Fig. 1 Tsukuba 32-m VLBI station.

1. Geospatial Information Authority of Japan
2. Advanced Engineering Service Co., Ltd.

Tsukuba Network Station

IVS 2015+2016 Biennial Report

Fig. 2 Ishioka Geodetic Observing Station.

Fig. 3 Geodetic VLBI network in Japan.

2 Component Description

The specifications of the antennas of Tsukuba 32 m and Ishioka are summarized in Table 1.

3 Staff

Regular staff members belonging to the VLBI group of GSI are shown in Table 2. In April 2015, Jiro KURODA was replaced by Ryoji KAWABATA, Shinobu KURIHARA was replaced by Takahiro WAKASUGI, and Masayoshi ISHIMOTO joined the group for operation of the stations. In April 2016, Kojin WADA was replaced by Basara MIYAHARA as a supervisor, and Tomoo TOYODA, and Michiko UMEI joined the group in order to take over the work of Yoshihiro FUKUZAKI. Primary routine operations were outsourced to a private company, Advanced Engineering Service Co., Ltd. (AES). Syota MIZUNO and Takafumi ISHIDA were replaced by Katsumi NUMAJIRI and Masatoshi NAKAGAWA as the operators in April 2016.

Table 1 Specifications of the Tsukuba 32-m and Ishioka 13-m antennas.

Antenna	Tsukuba 32 m	Ishioka 13 m
Owner and operating agency	GSI	GSI
Year of construction	1998	2014
Radio telescope mount type	Az-El	Az-El
Antenna optics	Cassegrain	Ring focus
Diameter of main reflector	32 m	13.2 m
Azimuth range	10-710°	-70-430°
Elevation range	5-88°	0-90°
Az/El drive velocity	3°/sec	12°/sec
Tsys at zenith (X/S)	50 K / 65 K	52 K / 49 K
SEFD (X/S)	320 Jy / 360 Jy	1500 Jy / 1400 Jy
RF range (X)	7780-8980 MHz	8180-8980 MHz
RF range (S with BPF)	2215-2369 MHz	2200-2400 MHz
RF range (Broadband)	–	3-14 GHz
Recording terminal (X/S)	K5/VSSP32 ADS3000+ with DDC	K5VSI ADS3000+ with DDC
Recording terminal (Broadband)	–	K6/iDAS

Table 2 Member list of the VLBI group of GSI (2016).

Name	Main Function
Basara MIYAHARA	Supervisor
Ryoji KAWABATA	Management, IVS Directing Board member, The secretary of AOV
Masayoshi ISHIMOTO	Operation
Takahiro WAKASUGI	Correlation, Analysis
Tomoo TOYODA	Outreach, Co-location
Michiko UMEI	Operation
Katsumi NUMAJIRI	Operation (AES)
Masatoshi NAKAGAWA	Operation (AES)
Toshio NAKAJIMA	System engineer (NTT-ATC)

4 Current Status

4.1 Geodetic VLBI Observations

The number of regular sessions of GSI stations designated by the IVS Master Schedules of 2015 and 2016 are shown in Table 3. Tsukuba 32 m participated in 139 24-hour VLBI sessions and 368 Intensive one-hour sessions for dUT1 measurement including 66 INT1 sessions as a replacement for the Kokee station. Ishioka participated in 61 24-hour VLBI sessions, 31 Intensive one-hour sessions, and three international broadband sessions (see Section 4.2). The other GSI antennas, Chichijima and Aira, participated in ten 24-hour VLBI sessions by the end of March 2015.

Table 3 Number of regular sessions observed by GSI in 2015 (left) and 2016 (right).

Sessions	Tsukuba 32-m	Ishioka	Aira	Chichijima
IVS-R1	42 / 50	7 / 25	–	–
IVS-T2	6 / 6	3 / –	1 / –	1 / –
APSG	2 / 2	– / 1	–	–
AOV	6 / 6	6 / 2	1 / –	–
JADE	18 / –	17 / –	4 / –	2 / –
JAXA	1 / –	–	1 / –	–
IVS-INT1	– / 66	–	–	–
IVS-INT2	102 / 100	– / 31	–	–
IVS-INT3	50 / 50	–	–	–
IVS-VGOS	– / –	– / 3	–	–

4.2 Broadband Observations

Ishioka carried out the first international collaborative broadband observing with both the Hobart 12-m antenna in Australia and the Kashima 34-m antenna in Japan in August 2016. The first fringes of the international broadband observing were detected between Ishioka and Hobart. In the observing, we used an AD sampler, K6/GALAS, developed by NICT (Sekido et al., 2015) instead of our frequency Up-Down Converter and our new sampler, K6/iDAS.

In addition to the first observing, Ishioka participated in three VGOS Trial sessions in August and September 2016. Fringes were not detected at Ishioka in the first Trial session. However, in the latter two sessions, fringes were successfully detected, and they were the first fringes for our new system with our frequency Up-Down Converter and an AD sampler, ADS3000+. This means that the equipment of Ishioka is compatible with that of the other IVS stations which participated in the Trial sessions. Our new sampler, K6/iDAS, is undergoing validation and will be used for future broadband sessions after the validation in the near future.

4.3 Co-location Survey at Tukuba 32-m and Ishioka

In January 2015, we performed a field co-location survey at Ishioka in order to measure accurate relative positions between the reference points of the Ishioka 13-m VLBI antenna and an antenna of a GNSS station which is planned to be an IGS tracking station. The relative position of the two points was determined with precisions of 0.6 mm in horizontal and 0.4 mm in vertical, respectively. In October 2016, we also performed a field co-location survey at Tsukuba 32 m. This was the last opportunity for Tsukuba 32 m to conduct a co-location survey. The data is still undergoing processing, and the latest local tie will be available in March 2017.

5 Ishioka as a Successor to Tsukuba 32 m

Operation of the Tsukuba 32 m was terminated at the end of 2016, and it will be dismantled by the end of March 2017. In 2017, Ishioka continues to participate in S/X legacy 24-hour and Intensive sessions as a successor to the Tsukuba 32 m and also participates in IVS VGOS campaign sessions. We are planning to increase opportunities to participate in the VGOS campaign sessions depending on the schedule planned by IVS.

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Nanshan IVS Biennial Report for 2015 and 2016

Wenjun Yang, Hua Zhang, Lang Cui, Xiang Liu, Peng Li, Guanghui Li

Abstract This report briefly introduces general information about the newly upgraded NanShan Radio Telescope (NSRT), the status of the VLBI backend, and the staff involved in VLBI activities. The report also summarizes the IVS observations with NSRT during 2015 and 2016.

1 General Information

The NanShan Radio Telescope (NSRT) is located in the Eurasia hinterland (about 70 km south of Urumqi) and is operated by the Xinjiang Astronomical Observatory (XAO), at the Chinese Academy of Sciences (CAS). After its active service for about 20 years, the NSRT received an overall upgrade, including the primary/secondary reflectors, the receiver cabin, the Azimuth track, and so on. The NSRT reconstruction project started in early 2014 and finally finished in late 2015. The new telescope aperture is now 26 meters, one meter larger than the old one. The NSRT is currently equipped with L-, S/X-, C-, and K-band receivers and a Q-band receiver is on the way. Figure 1 shows the new NSRT, and Table 1 lists the main properties of the antenna. In late 2015, the antenna parameters were measured systematically to involve the telescope in scientific observing as soon as possible. During 2016, the telescope participated in most of the EVN and IVS experiments and some of the EAVN commissioning, as well as in single-dish observations.

Xinjiang Astronomical Observatory (XAO), CAS

XAO-Nanshan Network Station

IVS 2015+2016 Biennial Report

Fig. 1 The new NanShan 26-m Radio Telescope (NSRT).

2 Upgrades of VLBI Backend Systems

In late 2016, the DBBC2 was set up (see Figure 2) and employed in test observations. The clear fringes and good SNRs of the commissioning observations suggest that the upgrade of the digital VLBI backend has been successful at the Nanshan Station. The DBBC2+Mark5B, as the main VLBI backend system of NSRT, will be involved in the formal IVS observations and other VLBI sessions in 2017. The Field

Table 1 The properties of new NSRT.

Telescope Name	NanShan Radio Telescope (NSRT)
Coordinates	87°10.67′ E, +43°28.27′ N
Antenna Mount	Azimuthal (El. Over Az.)
Telescope type	Shaped Cass.
Diameter of main reflector	26 m
Diameter of sub-reflector	3 m
Seat-rack type	Azimuth-pitching ring
Surface accuracy	0.4 mm (rms)
Pointing precision	10″(rms)
Receivers for Geodetic obs.	3.6 cm/13 cm

System was upgraded to version FS-9.11.8 and the Mark5B/B+ software up to SDK9.4.0, and the program Jive5ab was installed at the end of 2016. In addition, we purchased a set of RDBE and Mark 6 devices, which are still in testing, to be used for future observations.

3 Staff

The staff at Nanshan Station consists of about 20 people, including telescope operators; technical personnel for receivers, electronics, and mechanics; scientists, and administrative personnel. In Table 2, we list the persons involved in VLBI activities.

Table 2 Staff related to VLBI activities currently at Nanshan Station.

Name	Function	Contact
Lang Cui	VLBI friend/support scientist	cuilang@xao.ac.cn
Wenjun Yang	VLBI duty engineer/operator	yangwj@xao.ac.cn
Hua Zhang	VLBI duty engineer/operator	zhangh@xao.ac.cn
Peng Li	VLBI operator	lipeng@xao.ac.cn
Guanghui Li	VLBI operator	ligh@xao.ac.cn
Xiang Liu	VLBI support scientist	liux@xao.ac.cn

4 Geodetic VLBI Observations

In total, the NSRT participated in 32 24-hour regular IVS sessions during the years 2015 and 2016, as well as the EVN, Eastern Asia VLBI Network (EAVN), and Chinese VLBI Network (CVN) observations. The detailed information of IVS sessions including NSRT is listed in Table 3.

Fig. 2 The mounted DBBC2 at Nanshan station.

Acknowledgements

The NSRT is operated by the Xinjiang Astronomical Observatory (XAO), CAS. The reconstruction of NSRT was partly supported by the Chinese Lunar Exploration Project. The VLBI activities of NSRT are partly supported by Xinjiang Key Laboratory of Radio Astrophysics and Key Laboratory of Radio Astronomy, CAS.

Table 3 IVS observations at Nanshan Station during 2015 and 2016.

No.	epoch	code	obs.time	quality	Rate(Mbps)	format
1	2015-024 UT18:30	R4673	24	—	—	—
2	2015-080 UT00:30	Aov001	24	0%	128	MK5B
3	2015-085 UT18:30	R4680	24	0%	128	MK5B
4	2015-244 UT17:30	Apsg36	24	—	—	—
5	2015-246 UT18:30	R4703	24	—	—	—
6	2015-269 UT00:00	Aov005	24	—	—	—
7	2015-314 UT17:30	T2107	24	99.2%	128	MK5B
8	2015-342 UT17:30	Apsg37	24	99.3%	128	MK5B
9	2015-350 UT18:00	Aov006	24	0%	128	MK5B
10	2015-356 UT17:00	R4719	24	97.2%	128	MK5B
11	2016-007 UT18:30	R4721	0	0%	128	MK5B
12	2016-011 UT06:30	Aug020	0	0%	128	MK5B
13	2016-033 UT17:30	Aov007	24	99.9%	128	MK5B
14	2016-035 UT18:30	R4725	24	NOT CORR	128	MK5B
15	2016-076 UT18:00	Aov008	24	99.8%	128	MK5B
16	2016-077 UT18:30	R4731	24	98.8%	128	MK5B
17	2016-083 UT18:30	R4732	24	97.9%	128	MK5B
18	2016-132 UT17:00	Aov009	24	98.3%	128	MK5B
19	2016-173 UT17:30	T2111	24	96.1%	128	MK5B
20	2016-189 UT18:30	R4747	24	NOT CORR	128	MK5B
21	2016-194 UT17:30	Aua011	24	NOT USED	128	MK5B
22	2016-196 UT18:30	R4748	24	72%	128	MK5B
23	2016-208 UT17:30	Apsg38	24	98.7%	128	MK5B
24	2016-209 UT18:00	Aov010	24	98.5%	128	MK5B
25	2016-222 UT17:30	Aua012	24	99.7%	128	MK5B
26	2016-238 UT18:30	R4754	24	99.8%	128	MK5B
27	2016-264 UT17:00	Aov011	24	NOT USED	128	MK5B
28	2016-272 UT18:00	Apsg39	24	98.9%	128	MK5B
29	2016-286 UT17:30	Aov012	24	NOT CORR	128	MK5B
30	2016-320 UT17:30	T2114	24	??%	128	MK5B
31	2016-336 UT18:30	R4768	24	NOT CORR	128	MK5B
32	2016-354 UT16:30	Rd1613	24	??%	128	MK5B

New Zealand VLBI Station, Warkworth

Stuart Weston, Tim Natusch, Lewis Woodburn, Ben Hart, Sergei Gulyaev

Abstract The Warkworth Radio Astronomical Observatory is operated by the Institute for Radio Astronomy and Space Research (IRASR), AUT University, Auckland, New Zealand. Here we review the characteristics of the VLBI station facilities and report on a number of activities and technical developments in 2015/6.

1 General Information

The Warkworth Radio Astronomical Observatory, for which a panorama photo is shown in Figure 1, is located some 60 km north of the city of Auckland, near the township of Warkworth. Specifications of the Warkworth 12-m and 30-m antennas are provided in Table 1. The 12-m radio telescope is equipped with an S/X dual-band dual-circular polarization feed at the secondary focus and an L-band feed at the prime focus. Backend data digitizing is handled by a digital base band converter (DBBC) manufactured by the HAT-Lab, Catania, Italy. The 30-m radio telescope is currently equipped with an uncooled C-band dual-circular polarization receiver. The station frequency standard is a Symmetricom Active Hydrogen Maser MHM-2010 (75001-114). Mark 5B+ and Mark 5C data recorders are used for data storage and streaming of recorded data off site. The observatory network is directly connected to the national network provided by Research and Education Advanced Network New Zealand Ltd. (REANNZ) via a 10 Gbps fiber link to the site [1].

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Warkworth Network Station

IVS 2015+2016 Biennial Report

2 Component Description

2.1 The 12-m Antenna: Progress and Issues

In late 2016, the 12 m was out of commission due to the jack screw boot being ingested by the elevation bevel gear mechanism. Repair was effected by a local rigging firm that engineered a device using hydraulic rams. This can now be used in the future to support the dish at any elevation.

2.2 The 30-m Antenna: Progress and Issues

In cooperation with Lyrebird Antenna Research Pty Ltd., a new X-band feed for the 30 m that fits inside the existing C-band feed was designed [3], see Figure 2. We hope to have received this in the second quarter of 2017 and to start testing.

An L-band capability for the 30 m was experimented with over the last year. By removing the bottom three sections of the C-band feed and fitting an L-band feed horn with room temperature LNA to the opening, some success in receiving signals was achieved. At present the efficiency is very poor, of order 10%, but nonetheless may well prove adequate (given the 30 m's

Fig. 1: Photo of the two radio antennas at Warkworth on a frosty winter morning; on the left the 30 m and on the right the 12 m. In the background on the left hand side are the antennas belonging to Spark (formerly Telecom New Zealand). (Image courtesy of Stuart Weston).

Table 1: Specifications of the Warkworth 12-m and 30-m [2] antennas.

	12-m	30-m
Antenna type	Dual-shaped Cassegrain	wheel-and-track, Cassegrain beam-waveguide
Manufacturer	Cobham/Patriot, USA	NEC, Japan
Main dish Diam.	12.1 m	30.48 m
Secondary refl. Diam.	1.8 m	2.715 m
Focal length	4.538 m	10.380 m
Surface accuracy	0.35 mm	1.2 mm
Mount	alt-azimuth	alt-azimuth
Azimuth axis range	$90° \pm 270°$	$-179°$ to $+354°$
Elevation axis range	7.2° to 88°	6.0° to 90.1°
Azimuth axis max speed	5°/s	0.37°/s
Elevation axis max speed	1°/s	0.36°/s

collecting area) for some projects. GPS signals (L1, L2, and L5) were detected, and fringes to PKS 1921-293 between the Warkworth 30 m and the Hobart 26 m were detected. Useable bandwidth is from approximately 1.1 to 1.8 GHz. A noise diode system is currently being fitted that will allow more precise determination of efficiency, Tsys, and SEFD, and attempts to further optimize the system's performance will be ongoing.

2.3 Warkworth Network

In September 2016, the international circuits from New Zealand provided by REANNZ were upgraded to 100 Gbps bi-directional to the USA west coast and Australia. All Mk5s and DBBCs are being interconnected with fiber at 10 Gbps.

3 Current Status and Activities

2015 and 2016 have seen us settle into a steady number of IVS sessions on the 12 m. A break down of session types (i.e. OHIG, CRDS, APSG, R, and AUST) observed over this two year period is presented in Table 2.

In addition, both antennas are now active for Australian LBA sessions each semester, the choice of antenna being dependent on frequency. With the addition of the X-Band feed to the 30 m we would expect to see the LBA workload shift more to the 30-m antenna in the future. Also, cooperation with SpaceX and JAXA

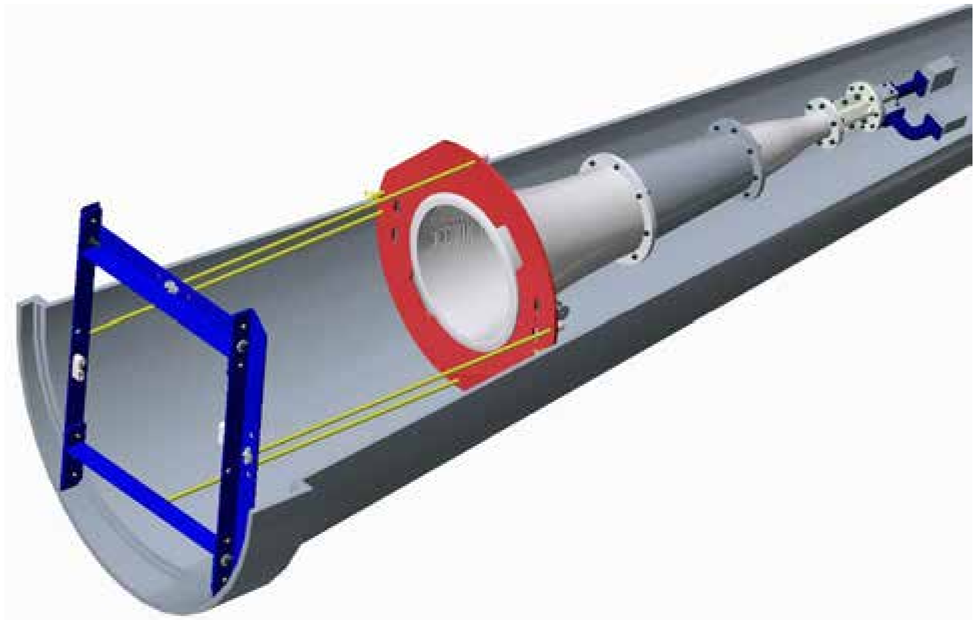

Fig. 2: The new X-Band feed and mechanism to lower it inside the existing C-Band feed. This is shown as horizontal in this paper, but it would be vertical in the actual installation. (Credit: Lyrebird Antenna Research Pty Ltd.).

Table 2: The 12 m IVS 2015/6 session participation.

Experiment	Number of sessions 2015	2016
APSG	1	2
AUG	6	3
AUV	6	5
AUA	6	6
CRDS	6	5
OHIG	6	3
R1	21	26
R4	29	28
T	1	2
Total	82	80

for spacecraft tracking has continued using the 12-m antenna.

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Westford Antenna 2015–2016 Biennial Report

Mike Poirier, Alex Burns

Abstract Technical information is provided about the antenna and VLBI equipment at the Westford site of the MIT Haystack Observatory, and about changes to the systems since the IVS 2014 Annual Report.

1 Westford Antenna at Haystack Observatory

Since 1981, the Westford antenna has been one of the primary geodetic VLBI sites in the world. Located ~70 km northwest of Boston, Massachusetts, the antenna is part of the MIT Haystack Observatory complex.

The Westford antenna was constructed in 1961 as part of the Lincoln Laboratory Project WestFord that demonstrated the feasibility of long-distance communication by bouncing radio signals off a spacecraft-deployed belt of copper dipoles at an altitude of 3,600 km. In 1981, the antenna was converted to geodetic use as one of the first two VLBI stations of the National Geodetic Survey Project POLARIS. Westford has continued to perform geodetic VLBI observations on a regular basis since 1981. Westford has also served as a testbed in the development of new equipment and techniques now employed in geodetic VLBI worldwide.

MIT Haystack Observatory

Westford Antenna

IVS 2015+2016 Biennial Report

Fig. 1 Aerial view of the radome and facilities of the Westford antenna. (For scale the diameter of the radome is 28 m.)

Table 1 Location and addresses of the Westford antenna.

Longitude	71.49° W
Latitude	42.61° N
Height above m.s.l.	116 m
MIT Haystack Observatory 99 Millstone Rd Westford, MA 01886-1299 U.S.A.	
http://www.haystack.mit.edu	

2 Technical Parameters of the Westford Antenna and Equipment

The antenna is enclosed in a 28-meter air-inflated radome constructed of a 1.2 mm thick teflon fabric (Raydel R-60) (see Figure 1). The major components of the VLBI data acquisition system at Westford include a VGOS broadband cryogenically-cooled front end, fiber optic RF downlinks, optical-to-RF

Fig. 2 View of the Westford antenna inside the radome. The VLBI VGOS receiver is located at the prime focus.

distributor, four Up/Down converters, four RDBEs and a Mark 6 recorder with expansion chassis, all controlled by a new PC running PCFS version 9.11.18. We are also running with our newly operational pointing interface, which allowed us to upgrade our new PCFS systems. We also have the MCI system, which monitors and logs parameters for key components in the system. The primary frequency standard on site is the NR-4 Hydrogen maser.

Westford also hosts the WES2 GPS site of the IGS network. A Dorne-Margolin chokering antenna is located on top of a tower at about 60 meters from the VLBI antenna. A LEICA GRX1200 Reference Station receiver completes the WES2 GPS site. ("The GPS receiver will soon be upgraded to a Septentrio unit by NOAA.")

Table 2 Technical parameters of the Westford antenna for geodetic VLBI.

Parameter	*Westford*
primary reflector shape	symmetric paraboloid
primary reflector diameter	18.3 meters
primary reflector material	aluminum honeycomb
feed location	primary focus
focal length	5.5 meters
antenna mount	elevation over azimuth
antenna drives	electric (DC) motors
azimuth range	$90^\circ - 470^\circ$
elevation range	$4^\circ - 87^\circ$
azimuth slew speed	$3^\circ\ s^{-1}$
elevation slew speed	$2^\circ\ s^{-1}$
	Frequency range 2–14 GHz
T_{sys} at zenith	*40–70 K*
aperture efficiency	0.25–0.60
SEFD at zenith	1800–4500 Jy

3 Westford Staff

The personnel associated with the geodetic VLBI program at Westford, and their primary responsibilities, are:

- Alex Burns: Technician, Observer
- Brian Corey: VLBI Technical Support
- Kevin Dudevoir: Pointing System Software
- Pedro Elosegui: Principal Investigator
- Colin Lonsdale: Site Director
- Glenn Millson: Observer
- Arthur Niell: VLBI Science Support
- Michael Poirier: Site Manager
- Ganesh Rajagopalan: RF Engineer

4 Standard Operations

From January 1, 2015, through December 31, 2016, Westford participated in 46 VGOS sessions. Westford also supported many short fringe tests with many worldwide stations in assisting their VGOS system configuration checkout.

Use of the Westford antenna is shared with the Terrestrial Air Link (TAL) Program operated by the MIT Lincoln Laboratory. In this project, Westford serves as the receiving end on a 42-km terrestrial air link designed to study atmospheric effects on the propagation of wideband communication signals at 20 GHz.

5 Research and Development

Presently we are running bi-weekly 24-hour sessions supporting the core VGOS stations. These sessions covered a wide range of focus from engineering testing to the standardizing of operational configuration formats supporting the expanding VGOS network.

6 Outlook

Westford expects to continue to support the VGOS operational series of 24-hour sessions, along with supporting new development, testing, and integration of VGOS systems around the world.

I expect over the next year we will install the last piece of the pointing system upgrade, which will give us better redundancy, and increased reliability for consistent operations.

Acknowledgements

I would like to thank Alex Burns, Pedro Elosegui, Arthur Niell, Ganesh Rajagopalan, and Chet Ruszczyk for their contributions to this report.

Funding for geodetic VLBI at Westford is provided by the NASA Space Geodesy Program.

Geodetic Observatory Wettzell – 20-m Radio Telescope and Twin Telescopes

Alexander Neidhardt [1], Christian Plötz [2], Gerhard Kronschnabl [2], Torben Schüler [2]

Abstract The Geodetic Observatory Wettzell, Germany contributed again very successfully to the IVS observing program during 2015 and 2016. Technical changes, developments, improvements, and upgrades were made to increase the reliability of the entire VLBI observing system. While the 20-m Radio Teslcope Wettzell (RTW, Wz) and the 13.2-m Twin radio Telescope Wettzell North (TTW1, Wn) are in regular S/X sessions, the 13.2-m Twin radio Telescope Wettzell South (TTW2, Ws) is equipped with a new VGOS receiving system. A main task was to bring this new technique into operation so that the first common, transatlantic VGOS observations became possible.

1 General Information

The Geodetic Observatory Wettzell (GOW) is jointly operated by the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, BKG) and the Research Facility Satellite Geodesy (Forschungseinrichtung Satellitengeodäsie, FESG) of the Technical University of Munich (TUM). The 20-m Radio Telescope in Wettzell (RTW) has been an essential component of the IVS since the year 1983. Meanwhile, the 13.2-m Twin radio Telescope Wettzell North (TTW1, Wn) also produces S/X-data as a regular station with about half of the load of RTW. Starting observing with the 13.2-m Twin radio Telescope Wettzell South (TTW2, Ws), which is the first VGOS antenna at Wettzell, the observatory is prepared for future requirements in the IVS.

In addition to the VLBI, an ILRS laser ranging system, several IGS GPS permanent stations, a large laser gyroscope G (ringlaser), and the corresponding local techniques, e.g., time and frequency, meteorology and super conducting gravity meters, are also operated. Meanwhile, Wettzell also operates a DORIS beacon and is now a complete fundamental station with all space geodetic techniques. A new project focuses on atmosphere monitoring and a new timing distribution, using compensated fiber-optic transfers, is under development together with external contractors. The developments also need to meet the requirements for future operation strategies, so that projects to increase automation and remote control are ongoing.

The GOW is also responsible for the AGGO system in La Plata, Argentina (which is the former station TIGO in Concepción, Chile) (see the separate report), and the German Antarctic Research Station (GARS) O'Higgins on the Antarctic peninsula (see the separate report).

2 Staff

The staff of the GOW consists of 34 members in total (plus ten student operators) on permanent and fixed-term contracts to do research, operations, maintenance, and repairs, or to improve and develop all systems of the GOW. The staff operating VLBI is summarized in Table 1.

1. Forschungseinrichtung Satellitengeodäsie (FESG), Technische Universität München
2. Bundesamt für Kartographie und Geodäsie (BKG)

RTW/TWIN Wettzell Network Station

IVS 2015+2016 Biennial Report

Table 1 Staff members of RTW.

Name	Affiliation	Function	Mainly working for
Torben Schüler	BKG	head of the GOW	GOW
Alexander Neidhardt	FESG	head of the microwave group, VLBI chief	RTW, TTW
Erhard Bauernfeind	FESG	mechanical engineer	RTW
Ewald Bielmeier	FESG	technician	RTW, TTW
Martin Brandl	FESG	mechatronic engineer (since Dec. 2016)	RTW, TTW
Gerhard Kronschnabl	BKG	electronic engineer (chief engineer TTW)	TTW, RTW
Christian Plötz	BKG	electronic engineer (chief engineer RTW)	RTW, TTW, O'Higgins
Raimund Schatz	FESG	software engineer	RTW
Walter Schwarz	BKG	electronic engineer	RTW, WVR)
Reinhard Zeitlhöfler	FESG	electronic engineer (until June 2016)	RTW
Armin Böer	BKG	electronic engineer	Infrastruct., RTW
Jan Kodet	FESG	appl. phys. engineer	DFG FOR1503 GNSS, time ref.
Apurva Phogat	BKG	MSc	correlation
Katharina Kirschbauer	FESG	student	Development monitoring
Gordon Klingl	FESG/ BKG	student (till June 2015)	Operator VLBI
Nadine Schörghuber	FESG/ BKG	student (since Oct. 2016)	Operator VLBI
Julia Weber	FESG/ BKG	student (till Sept. 2016)	Operator VLBI

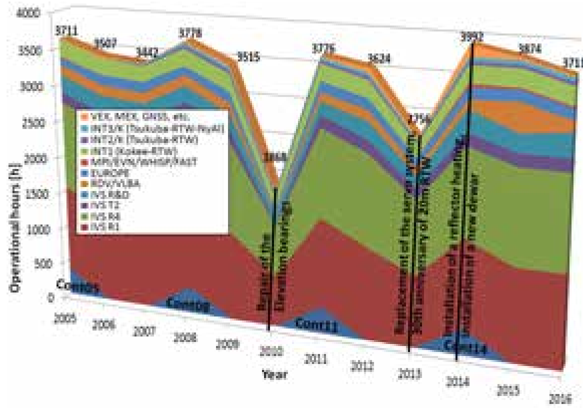

Fig. 1 Operational hours of the 20-m RTW since 2005.

3 20-m Radio Telescope Wettzell (RTW, Wz)

The 20-m RTW has been supporting the geodetic VLBI activities of the IVS and partly other partners, such as the EVN, for over 33 years now. All observed sessions in the reporting period are plotted in Figure 1. The telescope is still in a very good and stable state. The main priority was laid to the participation in all daily one-hour INTENSIVE-sessions (INT/K) in order to determine UT1-UTC. Some INT sessions were additionally planned and observed to characterize the baseline to the new VGOS site Ishioka, Japan. Using the Field System extension for remote control, weekend INTENSIVEs were partly done from remote. The antenna supported all main IVS 24h sessions and is still one of the main components of the IVS.

The complete VLBI data from the 20-m RTW is transferred with e-VLBI techniques to Bonn, Tsukuba, Haystack, Washington, and Socorro, using TSUNAMI or jive5ab on the 1 Gbit/sec connection of the Wettzell observatory.

In addition to the standard sessions, RTW was active in other special observations such as the tracking of the Mars Express (MEX) spacecraft and the RadioAstron satellite for the EVN. Progress was also made in tracking of Glonass and GPS satellites using an additional L-band receiver in the S-band path. Observations can be scheduled, observed, correlated, and analyzed directly here on location, using the telescope triple of the Wettzell observatory. On June 19, 2015 at 11:46:56 UT there was a rare event, where the asteroid Erida occulted a quasar, which was visble from Wettzell. The idea to use such occultations to compare and align the VLBI and Gaia based reference frames using asteroid occultations came from Finnish colleagues and was supported by the Wettzell team using the 20-m antenna. Even if the correlation of the data came to no result, it was an interesting research idea.

Another project, initiated by Chinese colleagues, was to observe the Rosetta spacecraft on September 20/21, 2015. Rosetta passed bright calibrator and other ICRF sources. The idea was to adjust the troposphere and ionosphere components of the delay model to get higher accuracy of the tracking. The schedule was prepared by colleagues at JIVE and the Wettzell 20-m antenna observed it together with over ten other telescopes worldwide. The 20-m antenna together with the northern twin telescope Wn also supported Wettzell high-speed VLBI session (WHISP) sessions in February 2015, August 2016, and November 2016, planned by colleagues of the Bonn university. WHISP sessions schedule a large number of observations to validate turbulence models in a local application. During WHISP, common clock tests were made where all telescopes were connected to maser EFOS-39. These tests were quite interesting to find issues in technical solutions for stable frequency transfers over hundreds of meters.

Monthly maintenance days were scheduled to give enough time to maintain the systems. Additionally, more extended service periods were necessary to exchange the lightening protection in July 2016, to repair leakage problems in the gears by the company AKIM in July 2015 and December 2016, and to clean the cover of the antenna tower, the backstructure, and the cabins by an external contractor starting in October 2016.

The dewar system, upgraded by the colleagues of the IVS Centro de Desarrollos Tecnológicos de Yebes, Spain, shows quite stable performance and reduced the maintenance tremendously. A second replacement dewar also was ordered at Yebes and was build and delivered in the reporting period. In April 2016, the latest maser maintenance and upgrade was made, so that all masers at the Wettzell observatory support now 5, 10, and 100 MHz. The NASA Field System is updated to the latest available version 9.11.18 and several DBBCs have been upgraded with new power supplies, up-to-date signal input modules, and software.

Fig. 2 Rescue exercise at the 20-m antenna.

In the early months of 2016, the TUM funded a conformity test of the 20-m antenna to follow the EC Machinery Directive. The conformity declaration was finished in April 2016, so that now all VLBI antennas ensure legal certainty in the sense of European right. Additional safety regulations also required to exercise rescue scenarios together with local fire departments and mountain rescue departments to rescue people from the 20-m antenna using a turnable ladder (see Figure 2).

4 13.2-m Twin Telescope Wettzell North (TTW1, Wn)

The Twin Telescope Wettzell project is Wettzell's realization of a complete VGOS conformity. Nevertheless, the northern antenna Wn is equipped with an S/X/Ka receiving system, which was a suitable solution in the days as no real VGOS feed was available. The northern antenna was the first available antenna supporting fast slewing modes in the IVS. It uses a DBBC2 or an ADS3000+ and a Mark 6B+ in the data acquisition rack. Meanwhile, the antenna is an accepted, full component of the IVS. The main focus is laid on classic S/X-observations. It observes half of the R1 and R4 sessions per year and all INT3 sessions. It was also used to support GNSS and RadioAstron observations. All observed sessions are plotted in Figure 3. Missing partners for Ka sessions reduce the possibilities to demonstrate geodetic Ka session.

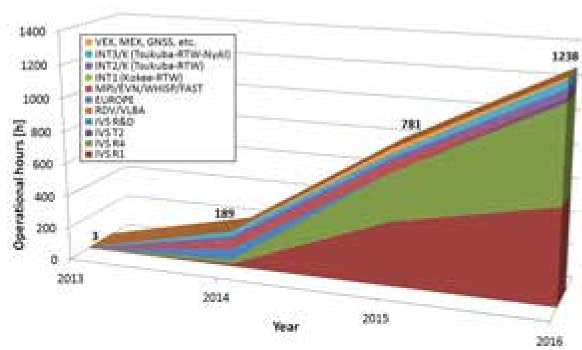

Fig. 3 Operational hours of the 13.2-m TTW1 since 2013.

A special session was scheduled and observed during the IVS General Meeting on March 10, 2016 where Wn was controlled from the lecture room at Hartebeesthoek, South Africa during a lesson to teach and train tasks necessary for a successful observation. To test fast-slewing modes and bring the fast antennas in the IVS network into common observations, Wettzell staff followed the idea to schedule and observe FAST sessions. The idea behind that was to use the fast slewing modes with classic S/X recording systems to get feedback about improvements coming from an increased number of sources per session. Another idea was to find issues and solutions for networks of new antennas with different equipment. Because of missing partners, unavailable systems, and partly insuperable difficulties, Wettzell stopped focusing on FAST sessions and focused on VGOS developments.

The Wn antenna runs quite stable and reliable. Only mechanical problems with the receiver mount in the cabin or electrical issues on the bus system for the encoders at low environmental temperatures had to be solved. A filter in the S-band was installed to improve the IF band quality, so that the DBBC can use its auto-gain control also for the S-band.

5 13.2-m Twin Telescope Wettzell South (TTW2, Ws)

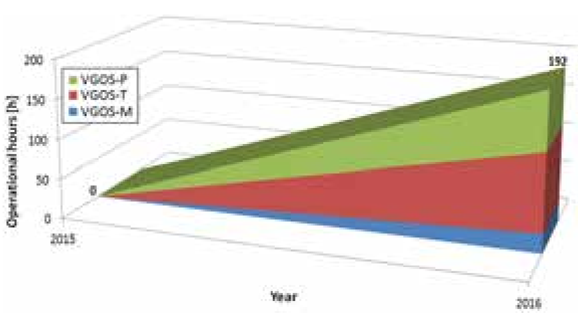

Fig. 4 Operational hours of the 13.2-m TTW2 since 2016.

The southern antenna Ws of the twin telescope is Wettzell's first VGOS compliant antenna using a broadband feed (Elevenfeed). It uses a tunable up-down-converter, two DBBC2, and a Mark 6 to record four bands in both polarizations. In October and November 2015, the feed cone and the feed could be installed after a long-lasting construction phase caused by external contractors. Using the in-house constructed receiver, first light was given in February 2016. Continuous updates, implementations, and constructions finally made it possible to run the first VGOS fringe test and session on April 28, 2016. Finding fringes was the first step towards a transatlantic VGOS baseline. In June 2016, successful fringes between GGAO12m Gs, Westford Wf, and Ws for all four VGOS bands and to Yebes Ys with a reduced band set were detected. The following months showed further issues with the stability of the recording system and the DBBCs. Upgrades of the power supplies in the DBBC brought a general stability. Nevertheless, more investigations are required to find all possible issues and bring the system into routine observations. Ws participated in all possible VGOS sessions (see Figure 4), even if only a few were finally correlated. Currently, all VGOS sessions are correlated at MIT Haystack Observatory, USA. Because of the huge data amount of about 16 or 32 Terabyte per day, the modules must be shipped again using parcel services. This delays any feedback from the correlator after each session.

The staff at Wettzell does continuous upgrades, implementations, and tests of the recording system. One major maintenance was necessary to replace a truss in the backstructure in July 2016, as it was busted due to frost damages in the past winter.

Fig. 5 The Wettzell triple of VLBI antennas: the Twin Telescope in the front and the 20-m telescope in the back (photo: Liu).

6 Other VLBI Relevant Activities

Besides antenna relevant tasks, staff from Wettzell participated in a special correlator training in Bonn. The need for such a special training came up, because BKG received funding for one project position to support correlation of local baselines between the three telescopes of the observatory. In combination with this project, VieVS was installed on different Matlab licenses to schedule own sessions. A DiFX software correlator was prepared and can be successfully used now. The same machine can also be used for analysis (e.g., nuSolve) so that the complete turnaround from planning to analyzing of sessions can now be performed.

Another project is the establishment of a 10 Gbit/sec transfer network, so that the baseband converter of all antennas can send their data to a selectable set of recording systems, consisting of Mark 6 and FlexBuff machines. It meets the requirements of the new VGOS sessions, but can also be used for classic S/X sessions. Each DBBC is connected to a FILA10G board, which is connected to a 10 Gbit/sec switch via fiber. The configuration of the FILA10G decides about the target machine where the data stream is recorded. The network should replace current setups with EVN PCs and connects the data acquisition in a safe way with the e-VLBI possibilities.

Fig. 6 The Wettzell observatory, in the rural area of the Bavarian forest, often offers possibilities to meet special visitors in front of the antennas.

To support co-location projects and the analysis of the connection quality of the systems to the time distribution, a common target was built, which carries a laser reflector and a radio source sending phase calibration pulses. Pointing the antennas to that common point and recording the received, external phase calibration tones, and enables conclusions about the timing. The plan is to observe the common target regularly to produce continuous timelines over longer time intervals.

The permanent survey of the reference point of the twin antennas continued using total stations on different pillars and 20 to 30 reflectors in the backstructure of the antenna. The goal is a continuous monitoring of the reference point over years.

In July and September 2015, tests with the DORIS system were used to find a suitable co-location position for a DORIS beacon, which does not interfere with the IF-bands of the radio antennas. After extended tests, a position was found behind the ring laser hill. The DORIS system was also just switched on for real satellite passages, so that sending times are limited during VLBI observations. DORIS is the fourth technique for a fundamental station and is an essential part for a GGOS core site.

7 Future Plans

Dedicated plans for the next reporting period are:

- Establishing automated observations and a suitable system monitoring;
- Finalizing changes to the DBBC at the 20-m RTW;
- Implementing VGOS compatibility for TTW1;
- Continuing improvements with the VGOS broadband system at TTW2 to participate in all VGOS sessions;
- Installing a DBBC3 and furthering FlexBuff systems; and
- Planning, observing, and analyzing own sessions.

Instituto Geográfico Nacional of Spain

Francisco Colomer [1], Pablo de Vicente [2], José Antonio López-Pérez[2], Laura Barbas[2], Félix Tercero[2], Javier López-Ramasco[2], Susana García-Espada[3,2], Rubén Bolaño-González[3,2], Luis R. Santos[4], José Antonio López-Fernández [2], Jesús Gómez-González [1]

Abstract The National Geographic Institute (IGN) of Spain has been involved in space geodesy activities since 1995. The 40-m radio telescope at Yebes Observatory has been a network station for IVS since 2008 and participates regularly in IVS sessions. IGN is developing an Atlantic Network of Geodynamical and Space Stations (project RAEGE). The first antenna saw its first light in 2014 at Yebes Observatory. Commissioning of a second antenna of RAEGE on Santa María island (Azores, Portugal) is being finished. First works for the third antenna in the Canary Islands have been initiated.

1 General Information

The National Geographic Institute of Spain (Instituto Geográfico Nacional, Ministerio de Fomento), has run geodetic VLBI programs at Yebes Observatory since 1995 and nowadays operates a 40-m radio telescope which is a network station for IVS (code "Ys"). IGN Yebes Observatory is also the reference station for the Spanish GNSS network and holds permanent facilities for gravimetry.

A new VGOS-type antenna, 13.2-m in diameter, has been built at Yebes as part of the RAEGE project (the acronym RAEGE stands for "Red Atlántica hispano-portuguesa de Estaciones Geodinámicas y Espaciales"). This antenna is operational and participates in the IVS VLBI broadband test observing under code "Yj" (RAEGYEB), even if not still not formally a network station in IVS. Detailed information on RAEGE is available on the Web at http://www.raege.net/

Since 2014, IGN Yebes Observatory has been a Technology Development Center for IVS. Activities are described in the corresponding contribution in this Biennial Report.

1. Instituto Geográfico Nacional (IGN), Spain
2. IGN Yebes Observatory, Spain
3. IGN RAEGE Santa María, Azores
4. Direção Regional das Obras Públicas e Comunicações (Azores, Portugal)

IGN-Yebes Network Station

IVS 2015+2016 Biennial Report

2 Current Status and Activities

Table 1 shows the observational sessions in which the IGN Yebes radio telescopes participated in 2015 (67) and 2016 (72). All the data were routinely transferred by Internet to the IVS correlators.

Table 1 Number of observational sessions at Yebes.

	Yebes 40-m	RAEGE 13.2-m	TOTAL
Sessions 2015	31	36	67
IVS R1	6	20	26
IVS R4	17	15	32
IVS T2	4	1	5
EUROPE	4	0	4
Sessions 2016	31	41	72
IVS R1	0	12	12
IVS R4	21	17	38
IVS T2	4	0	4
EUROPE	6	0	6
VGOS tests	0	12	12

During 2015 the 13.2-m telescope (Yj) performed 36 regular IVS sessions: 20 R1 sessions, 15 R4 sessions, and one T2 session. Regular observing started in February 2015 and finished in October 2015. Observing was discontinued because the tri-band receiver was dismounted and replaced by a broadband VGOS compatible receiver.

In April 2015, the Yebes 13.2-m antenna also took part in successful VLBI test observing at 32 GHz together with one of the Wettzell Twin radio telescopes [5]. Figure 1 shows the fringe plot of the Wettzell–Yebes baseline.

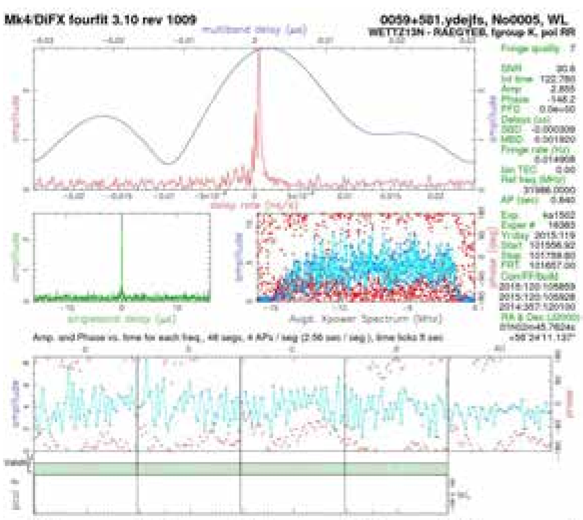

Fig. 1 Fringe plot for the Ws–Yj baseline at 32 GHz. These are the first detected fringes at 32 GHz between Wettzell and Yebes.

The tri-band Yj receiver was used as well to take part in six sessions organized by the Institute of Applied Astronomy in Saint Petersburg together with KVAZAR VGOS antennas between September and November 2015 to test recording rates of 2 Gb/s [4]. This high recording rate was also tested within the FAST project which aimed towards reducing the scan integration time while increasing the bandwidth and the number of scans.

Engineers at IGN Yebes Observatory have developed a VGOS-kind broadband receiver, which is installed and operational at the RAEGE 13.2-m radio telescope. Details may be found in the IGN Technology Development Center report, in this volume.

Once the broadband receiver was installed, in late 2015, first single dish observing was performed in March 2016. On 28 April 2016 the Yj telescope started taking part in test observing together with Wettzell, Westford, Kokee Park, and GGAO. The goal of this observing was to debug the hardware (frontend and backends) and the software at the stations and the correlator and to iron out the observational procedures. The observing required a Mark 6 recorder and one or two DBBC2s, depending on their availability. An internal report with information about the tests is in preparation [3].

Five sessions (ft6118, ft6126, ft6140, ft6161, and ft6188) were performed between April and July 2016. The first sessions with fringes in all four bands were in June 2016. Yj tested the four bands in two runs, because simultaneous bands were not possible because the two DBBC2 backends were not available simultaneously. All of these sessions were performed with one or two DBBC2s as backends. A second set of three experiments (vgt001, vgt002, and vgt003) was observed between July and August 2016 to debug and fix some issues with the DBBC2 firmware. The tests continued with sessions vgp001 and vgp002, but in this case Yj was using two RDBE-G backends mixed with one DBBC2 backend. In the last test performed in 2016, Yj used four RDBE-G backends. The test was fully successful; fringes are shown in Figure 2. The installation procedure and tests for the RDBE-G are summarized in [2].

The backends room, where the VLBI backends for the 40-m and 13.2-m radio telescopes are installed, was equipped, in June 2016, with an accurate air conditioning system that keeps the environment temperature with a precision of 0.2 degrees. That solved problems with the phase stability that had been present for several months. The positive impact on the geodetic observing has been visible since its installation.

The VDIF format started being used for geodetic VLBI on May 2016. Since then the 40-m radio telescope has started using Flexbuff as the recording equipment, and the data have been electronically transferred to the correlators via a Yebes high-speed connection fiber line to the Internet. A report on the usage of VDIF and scripts developed at Yebes for viewing data during experiments is available at our Web site [1].

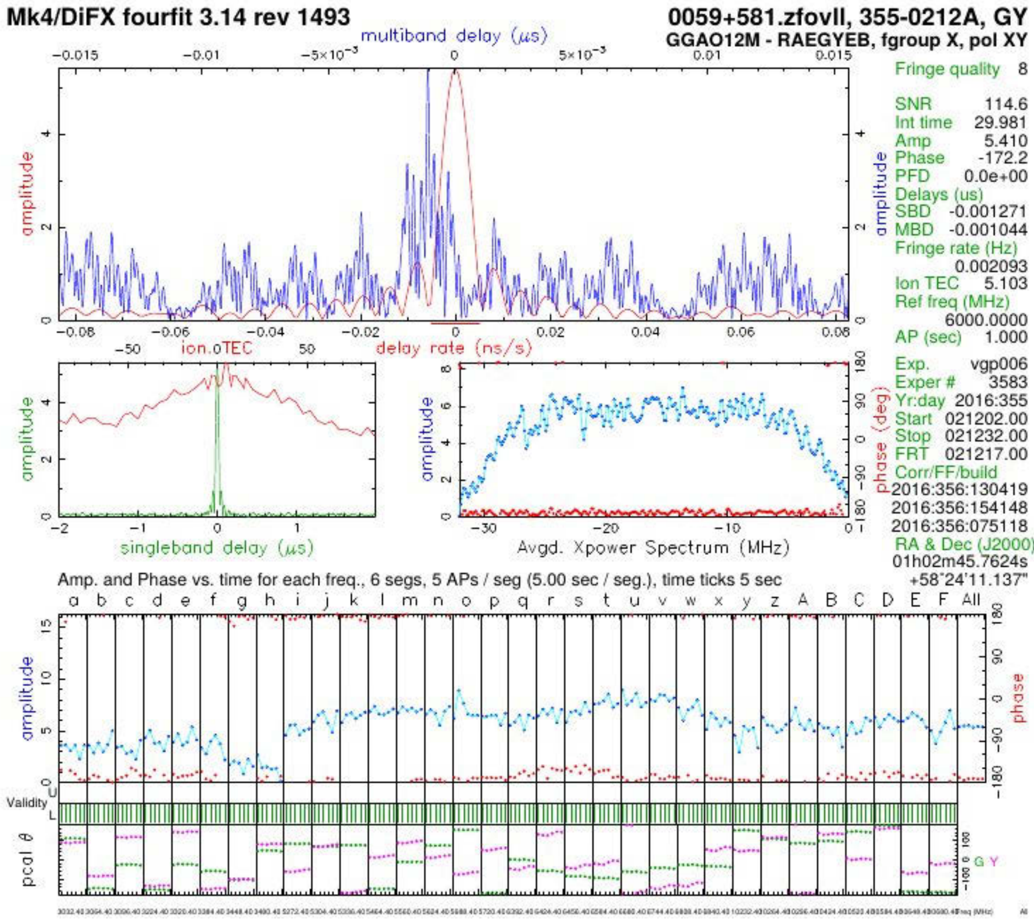

Fig. 2 Fringes in the four IFs of the VGOS broadband receiver with the 13.2-m "Jorge Juan" radio telescope at Yebes Observatory.

3 IGN Staff Working on VLBI Projects

Table 2 lists the IGN staff who are involved in space geodesy studies and operations. The VLBI activities are also supported by other staff members such as receiver engineers, computer managers, telescope operators, secretaries, and students.

Table 2 Staff in the IGN VLBI group (e-mail: **vlbitech@oan.es**).

Name	Role
Rubén Bolaño	Technical expert
Francisco Colomer	VLBI Project coordinator
Pablo de Vicente	VLBI technical coordinator
Susana García–Espada	geoVLBI expert
Jesús Gómez–González	IGN Deputy Director
José Antonio López–Fdez	Yebes Obs. & RAEGE Director
José Antonio López–Pérez	Receivers
Javier López–Ramasco	Geodesist
Félix Tercero	Antennas

4 Future Plans

Commissioning of the RAEGE station in Santa María is being performed, for an expected first light and start of observing in 2017.

Progress on the infrastructure works for the RAEGE station in the Canary Islands has been delayed, due to the need to perform tests for the suitability of the site. The erection of the antenna is expected in 2017, for a start of operations in 2018–2019.

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Zelenchukskaya Radio Astronomical Observatory 2015–2016 Report

Sergey Smolentsev, Andrei Dyakov, Dmitry Ivanov

Abstract The current status as well as activities in 2015 and 2016 of the Zelenchukskaya Radio Astronomical Observatory are considered.

1 General Information

The "Quasar" VLBI Network is a unique Russian astronomical instrument created in the Institute of Applied Astronomy of the Russian Academy of Sciences (IAA RAS). The Network consists of three observatories including Svetloe in the Leningrad Region, Badary in Eastern Siberia, and Zelenchukskaya in the Northern Caucasus, and the Data Processing Center in St. Petersburg. Svetloe Observatory was the first to be put into operation in 1999, the next was Zelenchukskaya in 2002 (Figure 1), and finally Badary in 2005. Each observatory is equipped with at least three co-located instruments of different techniques: VLBI, SLR, combined GNSS receivers, and the DORIS system (Badary observatory) [1]. The main instrument in each of three observatories is a 32-m radio telescope (RT-32), which provides a completely automatic process of observing radio sources and satellites in a radiometric or a radio interferometric mode. The main technical characteristics of the antennas are presented in Table 1. The RT-32 radio telescopes equipped with highly sensitive receivers provide signal amplification in 1.35 cm, 3.5 cm, 6 cm, 13 cm, and from 18 cm to 21 cm frequency bands in both circular polarizations. The baselines of the radio interferometer vary from 2,000 to 4,400 km. All observatories are linked by optical fiber lines and are equipped with identical hydrogen Time Standards, Water Vapor Radiometers, and meteorological stations, which are used by all types of observations.

Institute of Applied Astronomy of RAS

Zelenchukskaya Network Station

IVS 2015+2016 Biennial Report

Fig. 1 Zelenchukskaya Observatory.

2 Activities during the Past Two Years

Upgrading of the "Quasar" VLBI Network started in 2012. The aim of the upgrade was to create a Radio Interferometer of the new generation for improving the accuracy, reliability, and efficiency of providing the Earth rotation parameters to consumers in Russia and abroad. The Radio Interferometer of the new generation is designed to operate as part of the "Quasar" and international VLBI Networks. Currently, this new Radio Interferometer operates successfully and consists of two multi-band fast rotating Antenna Systems with

Table 1 Specifications of RT-32.

Mount	alt-azimuth
Configuration	Cassegrain
Subreflector scheme	asymmetrical
Main mirror diameter	32 m
Subreflector diameter	4 m
Focal length	11.4 m
Azimuth speed	$1.0\,^{\circ}/\mathrm{sec}$
Elevation speed	$0.5\,^{\circ}/\mathrm{sec}$
Limits by Az	$\pm 265^{\circ}$
Limits by El	$0^{\circ} - 85^{\circ}$
Axis offset	-9.7 ± 1.0 mm
Tracking accuracy	± 10 arcsec
Surface accuracy (RMS)	0.5 mm
Frequency range	1.4–22 GHz
Polarization	LCP + RCP

a mirror diameter of 13.2-m (RT-13), which were installed at the Zelenchukskaya (Figure 2) and Badary observatories in 2015 [2]. Table 2 presents some specifications of the RT-13 Antenna System, which meet all requirements of the VGOS program.

Table 2 Specifications of the RT-13.

Mount	alt-azimuth
Configuration	Cassegrain
Subreflector scheme	ringfocus
Main mirror diameter	13.2 m
Subreflector diameter	1.48 m
Focal length	3.7 m
Azimuth speed	$12.0\,^{\circ}/\mathrm{sec}$
Elevation speed	$6.0\,^{\circ}/\mathrm{sec}$
Limits by Az	$\pm 245^{\circ}$
Limits by El	$6^{\circ} - 109^{\circ}$
Axis offset	-0.1 ± 0.5 mm
Operation	24 h/7 d
Tracking accuracy	± 15 arcsec
Surface accuracy (RMS)	0.3–0.1 mm
Frequency range	2–40 GHz
The surface efficiency	> 0.7
Polarization	LCP + RCP

During 2015–2016, the RT-32 and RT-13 radio telescopes at Zelenchukskaya Observatory participated in both IVS and domestic (Ru-E, Ru-I, and R) VLBI observations. Activities of the observatory are presented

Fig. 2 The RT-13 Antenna of Zelenchukskaya Observatory.

in Tables 3 and 4. e-VLBI mode data transfer is used at the Zelenchukskaya for the domestic sessions. Since 2015, the RT-13 radio telescope participates in the following geodetic sessions:

- The 0.5–one-hour geodetic program in S/X bands for UT1 determination (“R”, on the baseline ZELRT13V–BADRT13V).
- The test geodetic program in X/Ka and S/X/Ka bands (“Ru-TEST”, on the baseline ZELRT13V–BADRT13V).
- The 23-hour geodetic program in S/X bands for improving the position data of the RT-13 antennas (“Ru-TEST”, all “Quasar” antennas).
- Miscellaneous test sessions, including international cooperation (“Ru-TEST”).

Table 3 VLBI observations of RT-32 at Zelenchukskaya Observatory.

Sessions	2015	2016
IVS-R4	25	19
IVS-T2	2	5
EUROPE	2	5
R&D	4	4
Ru-E	37	35
Ru-I	354	370

Table 4 VLBI observations of the RT-13 of Zelenchukskaya Observatory.

Sessions	2015	2016
R	137	1378

3 Future Plans

In the next two years, the Zelenchukskaya Observatory will continue to participate in IVS and domestic VLBI observations, upgrade the existing equipment, and replace the obsolete equipment.

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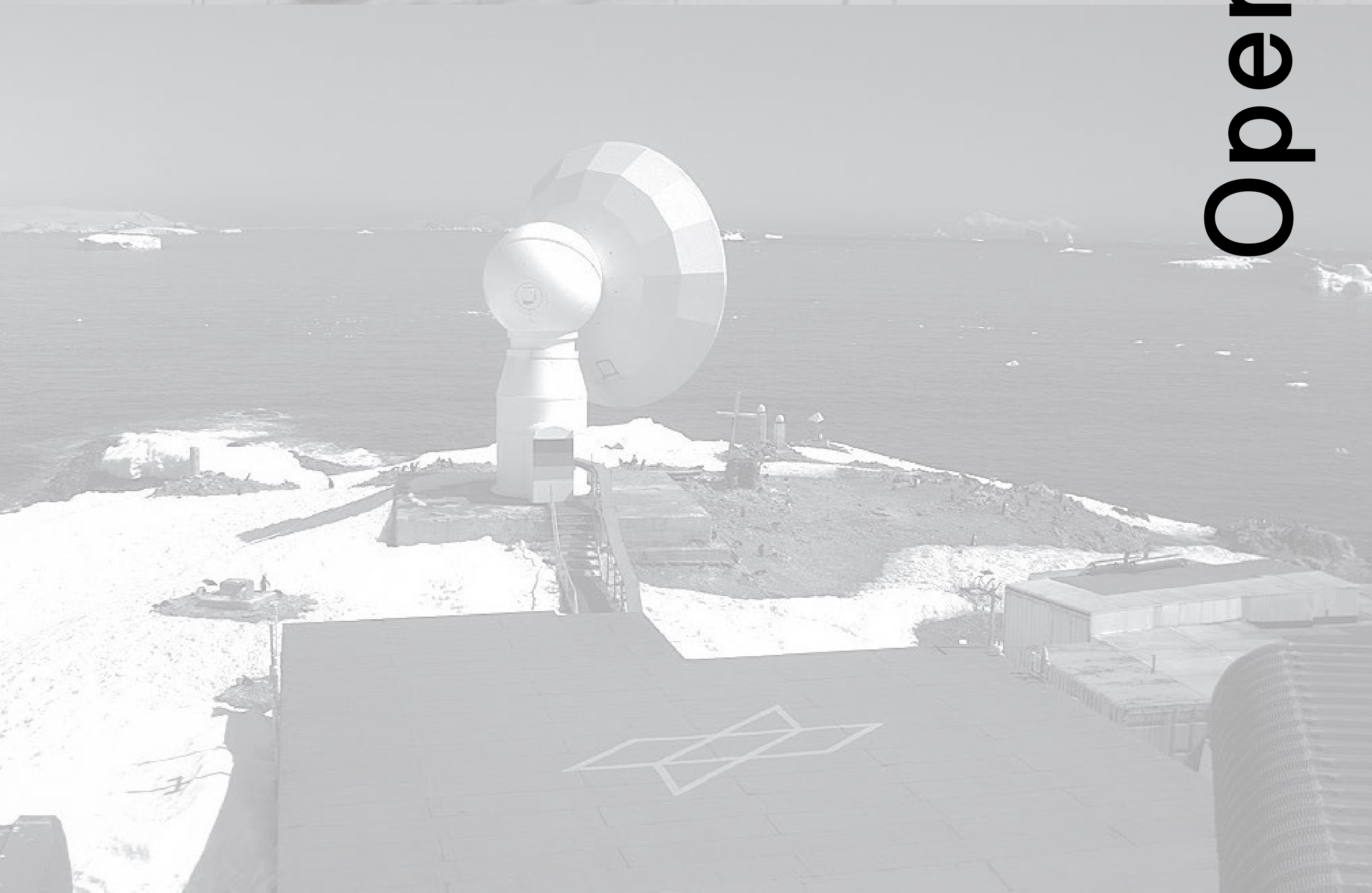
Operation Centers



Bonn Geodetic VLBI Operation Center

A. Müskens, A. Nothnagel

Abstract The IGGB Operation Center has continued to carry out its tasks of organizing and scheduling various observing sessions of the IVS-T2, IVS-OHIG, IVS-INT3, and EUROPE series.

1 Center Activities

The IGGB VLBI Operation Center is part of the Institute of Geodesy and Geoinformation of the University of Bonn, Nußallee 17, D-53115 Bonn, Germany. It has been organizing and scheduling VLBI observing sessions for more than thirty years. The work of the Operation Center is closely related to the Bonn Correlator. For this reason, distribution of the Mark 5 disk units to the stations after correlation and the extension of the Internet connection from previously 1 Gbps to 2 Gbps in Fall 2016 are the most costly parts of the operations. Below, we describe the activities related to individual observing programs.

- **IVS-T2 series**
  This series was observed roughly every second month (seven sessions each in 2015 and 2016) primarily for maintenance and stabilization of the VLBI terrestrial reference frame as well as for Earth rotation monitoring as a by-product. Each station of the global geodetic VLBI network is planned to participate in the T2 sessions at least once per year. In view of the limitations in station days, priority was given to strong and robust networks with many sites over more observing sessions. Therefore, generally 15 to 24 stations were scheduled in each session. The scheduling of these sessions has to take into account planning a sufficient number of observations for each baseline of these global networks.
  The recording frequency setup has always been 16 channels, with 4 MHz channel bandwidth and 360/80 MHz spanned bandwidth at X- and S-band, respectively. Considering that the standard setups of the majority of IVS sessions cover a wider spanned bandwidth and a higher sampling rate, it was decided to test which stations of the global IVS network are capable of this as well. So, in December 2016 we carried out a test experiment to check a higher recording mode. We observed with 256 Mpbs, 16 tracks, and a bandwidth of 8 Mhz/channel. Wideband was used with 720 Mhz spanned bandwidth at X-band and 140 Mhz at S-band, i.e., setting the sky frequencies to
  8212.99, 8252.99, 8352.99, 8512.99,
  8732.99, 8852.99, 8912.99, 8932.99 MHz and
  2225.99, 2245.99, 2265.99, 2295.99,
  2345.99, 2365.99 MHz.
  It turned out that several stations such as KASHIM11, KOGANEI, NOTO, CRIMEA, and the DSN stations can only observe the 360 MHz spanned bandwidth at X-band. Here, it was decided to record only the first four channels, i.e., 8212.99, 8252.99, 8352.99, and 8512.99 MHz still covering 300 MHz spanned bandwidth and producing a reasonable delay resolution function. The full 140 MHz spanned bandwidth at S-band was not covered in all cases, either. This session is being analyzed to figure out how to proceed with the T2 sessions in the future.

Institut für Geodäsie und Geoinformation der Universität Bonn

Bonn Operation Center

IVS 2015+2016 Biennial Report

- **Measurement of Vertical Crustal Motion in Europe by VLBI (EUROPE)**
  Since the late 1980s, a series of special sessions has been regularly scheduled in Europe for precise determination of station coordinates and for long term stability monitoring. In 2015 and 2016, six observing sessions were scheduled each year with NYALES20 (11 sessions), METSAHOV (3), DSS65A (7), SVETLOE (7), ZELENCHUKS (7), BADARY (7), EFLSBERG (4), WETTZELL (12), WETTZ13N (5 in tag-along mode), MEDICINA (7), MATERA (5), NOTO (8), ONSALA60 (9), YEBES40M (8), and CRIMEA (1). All sessions employed the narrow band frequency setup of 360/80 MHz with 16 channels and 4 MHz bandwidth, identical to the IVS-T2 sessions' setup. Beginning with the session of September 5, 2016 we started to increase the data rate to 256 Mbps with 16 tracks and a bandwidth of 8 Mhz/channel. We also increased the spanned bandwidth to 720 Mhz at X-band and 140 MHz at S-band. In 2017, we will also test a 512 Mbps setup in sessions called EUR-R&D.
- **Southern Hemisphere and Antarctica Series (OHIG):**
  In 2015 and 2016, six sessions of the Southern Hemisphere and Antarctica Series were organized. The purpose of these observations is the maintenance of the VLBI terrestrial reference frame (TRF) and monitoring of Earth rotation as a by-product. The recording frequency setup is 16 channels with 4 MHz channel bandwidth and a data rate of 128 Mbps spanning 360/80 MHz. Due to the fact that SYOWA is not able to deliver the recorded data for nearly one year after the observations, the correlation and the generation of the databases is always delayed considerably.
  In the OHIG sessions, the two Antarctic stations OHIGGINS (Germany) and SYOWA (Japan) were mostly scheduled with KATH12M (North Australia), YARRA12M (West Australia), HOBART12 and HOBART26 (Tasmania), WARK12M (New Zealand), HARTRAO and HART15M (South Africa), KOKEE (Hawaii, USA), and FORTLEZA (Brazil). Three sessions were observed in February 2015, three in November 2015, three in February 2016, and three in November 2016. In November 2015 and November 2016 the sessions, unfortunately, could only be observed without OHIGGINS due to receiver and dewar upgrades as well as to extreme wind velocities and logistical constraints. February 9, 2016, marks the date of the 100th OHIG session, which is quite a noteworthy occasion considering that mostly only six sessions were scheduled each year.
- **UT1 determination with near-real-time processing (INT3):**
  The basic INT3 network consists of NYALES20, TSUKUB32, and WETTZELL for rapid UT1 determination on Monday morning at 7:00 UT. SESHAN25 takes part on a monthly basis. In 2016, WETTZ13N started participating in a tag-along mode. 40 INT3 sessions in 2015 and 50 in 2016 were observed with the standard frequency setup of 256 Mbps with 16 tracks, 8 Mhz/channel, and 720/140 Mhz spanned bandwidth as in the R1/R4 sessions. Starting in September 2016, we increased the observing data rate and changed the frequency setup to 512 Mbps with 16 tracks, 8 Mhz/channel, 2-bit sampling, and 720/140 Mhz spanned bandwidth.
  The operations part of the INT3 sessions also includes rapid data transmission and correlation. The raw VLBI observation data of the four sites are transferred to the Bonn Correlator by Internet connections directly after the session is completed. The transmission rate is about 400-600 Mbps from Tsukuba and Wettzell, 300 Mbps from Seshan, and 100 Mbps from Ny-Ålesund. For the latter, the data rate is limited due to the use of a radio link for the first part of the distance. All transmissions share the "last mile", which is still limited to 1 Gbps because the second 1 Gbps line is restricted to local night time operations (see the Bonn Correlator Report, this issue).
  In the last two years, around 96% of the sessions were correlated and the databases delivered within the first four hours after the end of the observations. A further 2% were completed within the next 48 hours due to difficulties with networking hardware and/or station and processor problems.

2 Staff

Table 1 Personnel at IGGB Operation Center.

Arno Müskens	+49-228-525264	mueskens@mpifr.de
Axel Nothnagel	+49-228-733574	nothnagel@uni-bonn.de

CORE Operation Center 2015 & 2016 Biennial Report

Cynthia C. Thomas, Daniel S. MacMillan

Abstract This report gives a synopsis of the activities of the CORE Operation Center from January 2015 to December 2016. The report forecasts activities planned for the year 2017.

1 Changes to the CORE Operation Center's Program

The Earth orientation parameter goal of the IVS program is to attain precision at least as good as 3.5 μs for UT1 and 100 μas for pole position.

The IVS program, which started in 2002, used the Mark IV recording mode for each session. The IVS program began using the Mark 5 recording mode in mid-2003. By the end of 2007, all stations had been upgraded to Mark 5. Due to the efficient Mark 5 correlator, the program continues to be dependent on station time and media. The following are the network configurations for the sessions for which the CORE Operation Center was responsible in 2015 and 2016:

- IVS-R1 (2015): 52 sessions, scheduled weekly and mainly on Mondays, seven to 14 station networks
- RV (2015): Six sessions, scheduled evenly throughout the year, 13 to 15 station networks
- IVS-R&D (2015): ten sessions, scheduled monthly, six to 11 station networks
- IVS-R1 (2016): 52 sessions, scheduled weekly, seven to 14 station networks
- RV (2016): Six sessions, scheduled evenly throughout the year, 14 to 15 station networks
- IVS-R&D (2016): 13 sessions, scheduled monthly, four to 12 station networks

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CORE Operation Center

IVS 2015+2016 Biennial Report

2 IVS Sessions from January 2015 to December 2016

This section describes the purpose of the IVS sessions for which the CORE Operation Center is responsible.

- IVS-R1: During the period of January 2015 through December 2016, the IVS-R1s were scheduled weekly with seven to 14 station networks. During that time, 20 different stations participated in the IVS-R1 network, but there were only seven stations that participated in at least half of the scheduled sessions during 2015 and 2016—Wettzell (52, 52), Ny-Ålesund (48, 45), Katherine (43, 39), Yarragadee (42, 42), Tsukuba (41, 49), Sejong (36, 38), and Fortaleza (32, 41).
  The purpose of the IVS-R1 sessions is to provide weekly EOP results on a timely basis. These sessions provide continuity with the previous CORE series. The "R" stands for rapid turnaround because the stations, correlators, and analysts have a commitment to make the time delay from the end of data recording to the analysis results as short as possible. Participating stations are requested to ship disks to the correlator as rapidly as possible or to transfer the data electronically to the correlator using e-VLBI. The "1" indicates that the sessions are mainly on Mondays. The time delay goal is a maximum of 15 days from the end of data

Table 1 Median (first line) and variability (second line) of EOP formal uncertainties.

Session Type	Num	X-pole (μas)	Y-pole (μas)	UT1 (μs)	DPSI (μas)	DEPS (μas)
R1	52,52,49	43,34,39	44,40,41	2.2,2.1,2.2	82,60,75	32,26,28
		12,10,15	10,6,10	0.6,0.3,0.7	30,26,33	13,11,13
R4	49,50,51	45,36,44	45,40,45	2.3,2.1,2.3	90,70,100	37,27,40
		20,12,20	19,8,14	1.0,0.4,1.0	50,32,45	19,12,20
RV	6	39,38,41	40,41,40	2.1,2.6,2.1	63,77,66	25,30,30
		4,4,5	3,2,6	0.3,0.4,0.3	6,5,19	5,3,5
CONT11	15	27	28	1.3	39	16
		0.7	0.7	0.1	3	1
CONT14	15	28	30	1.4	40	14
		0.7	0.3	0	3	1

For the R1s, R4s, and RVs the values are for 2016, 2015, and 2014 in that order. The number of sessions listed are the number in our operational solution.

recording to the end of correlation. Forty-two percent of the IVS-R1 sessions were completed in 15 or fewer days during 2015. The remaining 58% were completed in 16 to 41 days [16 days (seven), 17 days (five), 18 days (one), 20 days (four), 21 days (two), and 22 days (five), with the remaining six sessions being processed in the range of 25 through 41 days]. During 2016 the percentage of R1 sessions being processed within 15 days increased from 42% to 85%. There were only eight sessions that were completed in 16 to 21 days.

- RV: There are six bi-monthly coordinated astrometric/geodetic experiments each year that use the full ten-station VLBA plus up to five geodetic stations. These sessions are being coordinated by the geodetic VLBI programs of three agencies: 1. USNO performs repeated imaging and correction for source structure; 2. NASA analyzes this data to determine a high accuracy terrestrial reference frame, and 3. NRAO uses these sessions to provide a service to users who require high quality positions for a small number of sources. NASA (the CORE Operation Center) prepares the schedules for the RDV sessions.
- R&D: The purpose of the ten R&D sessions in 2015, as decided by the IVS Observing Program Committee (OPC), was to vet sources for GAIA proposal (RD1501, RD1502, RD1503, RD1504, RD1508, and RD1509) and observe the Chang'E-3 Lander with VLBI (RD1505, RD1506, RD1507, and RD1510).
  The purpose of the R&D sessions in 2016, as decided by the OPC, was to vet sources for GAIA proposal (RD1602, RD1605, RD1606, RD1607, RD1611, and RD1612), observe the Chang'E-3 Lander (RD1601, RD1604, RD1609, and RD1613), evaluate a new strategy for scheduling the INT1 sessions (RD1608 and RD1610), and test the theoretical model for gravitational delay of propagation of light through the field of the Sun. Three extra R&Ds were added during 2016 to ensure that approved proposals were supported.

3 Current Analysis of the CORE Operation Center's IVS Sessions

Table 1 provides the median formal Earth Orientation Parameter (EOP) errors for the R1, R4, and RV for 2014, 2015, and 2016. To give an idea of how much variation there is, the standard deviation of the formal errors for each case is also shown. For comparison, the formal error statistics for the CONT11 and CONT14 are also given. The R1 session formal uncertainties were better in 2015 than in either 2014 or 2016. This is especially clear for polar motion and nutation, where uncertainties were 20-35% better than in 2014 and 2016. This is also reflected in the standard deviations of these errors, which are 30-60% less in 2015. It is most likely due to a more stable global network of stations during 2015.

The RV X-pole, Y-pole, and UT1 formal errors are comparable to the uncertainties of the R1 and R4 experiments. On the other hand, nutation uncertainties are significantly better. This is probably due to the fact that

RV sessions have a larger global network that is more stable from session to session. The formal uncertainties in 2016 were generally better than in 2014–2015.

For comparison, we also included the formal uncertainties for the CONT11 and CONT14 campaigns. These are significantly better than for any of the other networks. Median polar motion uncertainties are at or below 30 μas, and the UT1 uncertainties are only 1.2-1.3 μs or equivalently 18-20 μas.

Table 2 shows EOP biases and WRMS differences with respect to the IGS Finals series for the R1, R4, and RV series and the CONT11 and CONT14 series. To do this calculation, we used the latest operational GSFC EOP series based on the new GSFC 2016a quarterly solution. This solution used the new ITRF2014 reference frame model, which includes Earthquake site models for co-seismic offsets and post-seismic deformation. In doing this, we no longer estimated post-seismic station positions for TSUKUB32 and TIGOCONC. This has the effect of reducing formal uncertainties as well as allowing these stations to contribute fully to EOP estimation. We have found that this leads to better agreement between VLBI and IGS polar motion.

The WRMS differences were computed after removing a bias, but estimating rates does not affect the residual WRMS significantly. Both the R1 and R4 series have better WRMS agreement in X-pole, Y-pole, and LOD for 2015 than for the corresponding full series from 2000 to 2014. The WRMS agreement was clearly better in 2015 than in 2016. The X-pole biases (30-60 μas)and Y-pole biases (110-130 μas) of the R1 and R4 sessions relative to IGS are significant and are likely due to reference frame bias. The biases for the CONT and RV sessions are at a similar level, indicating an overall reference frame bias of the VLBI solution relative to the IGS frame.

In both 2015 and 2016, the WRMS agreement for polar motion was better than for the full period of RV observing since 2000. The RVs have the best agreement with IGS of all the series that have observed over the full period 2000–2014.

For comparison with the 2015–2016 operational R1 and R4 sessions discussed here, we included the statistics for the CONT11 and CONT14 campaigns. These sessions clearly have the best WRMS agreement with IGS. The X-Pole agreement with IGS for CONT14 is significantly better than for CONT11; otherwise, the WRMS differences are comparable. It is expected that the CONT networks will perform better than the operational R1 and R4 sessions because 1) the CONT sessions have better geometry and 2) the CONT networks are unchanged over the period of continuous observing.

4 The CORE Operations Staff

Table 3 lists the key technical personnel and their responsibilities so that everyone reading this report will know whom to contact about their particular question.

5 Planned Activities during 2017

The CORE Operation Center will continue to be responsible for the following IVS sessions during 2017:

- The IVS-R1 sessions will be observed weekly and recorded in Mark 5 mode. There is a strong possibility that mixed mode will be observed and processed. Westford may be added to the network as a Mark 6 station.
- The IVS-R&D sessions will be observed ten times during the year.
- The RV sessions will be observed six times during the year.
- The CONT17 Campaign will be observed with three networks observing simultaneously. There will be a regular legacy station network observing with a frequency sequence of 512 Mbps, a VLBA plus a few legacy stations observing with a frequency sequence of 256 Mbps, and a broadband network. The broadband network will not observe for the full 15 days.

Table 2 Offset and WRMS differences (2016 and 2015) relative to the IGS Finals combined series.

Session Type	Num	X-pole Offset (μas)	X-pole WRMS (μas)	Y-pole Offset (μas)	Y-pole WRMS (μas)	Length Of Day (LOD) Offset (μs/d)	Length Of Day (LOD) WRMS (μs/d)
R1	52,52(770)	40,56(10)	63,62(87)	114,116(136)	81,74(80)	0.4,-1.9(0.5)	13.1,16.0(16.3)
R4	49,50(761)	30,33(-19)	85,56(91)	135,132(141)	99,71(99)	4.7,-2.8(1.5)	18.2,13.4(17.5)
RV	6(102)	63,56(44)	77,111(86)	96,74(142)	68,80(73)	5.7,8.7(0.3)	12.2,9.5 (13.5)
CONT11	15	-10	26	107	29	7.1	5.7
CONT14	15	27	19	175	30	1.9	5.3

Values are for 2016 and then 2015 and in parentheses for the entire series (since 2000) for each session type.

Table 3 Key technical staff of the CORE Operations Center.

Name	Responsibility	Agency
Dirk Behrend	Organizer of CORE program	NVI, Inc./GSFC
Brian Corey	Analysis	Haystack
John Gipson	SKED program support and development	NVI, Inc./GSFC
Frank Gomez	Software engineer for the Web site	Raytheon/GSFC
David Gordon	Analysis	NVI, Inc./GSFC
Ed Himwich	Network Coordinator	NVI, Inc./GSFC
Dan MacMillan	Analysis	NVI, Inc./GSFC
Katie Pazamickas	Maser maintenance	Harris Corporation
Heidi Riesgo	Receiver maintenance	Harris Corporation
David Rubincam	Procurement of materials necessary for CORE operations	NASA/GSFC
Braulio Sanchez	Procurement of materials necessary for CORE operations	NASA/GSFC
Cynthia Thomas	Coordination of the Master Observing Schedule and preparation of observing schedules	NVI, Inc./GSFC

NEOS Operation Center

David M. Hall

Abstract This report covers the activities of the NEOS Operation Center at USNO for 2015 and 2016. The Operation Center schedules IVS-R4 and the INT1 Intensive sessions.

1 VLBI Operations

NEOS operations in the period covered consisted, each week, of one 24-hour duration IVS-R4 observing session, on Thursday-Friday, for Earth Orientation, together with five daily one-hour duration "Intensives" for UT1 determination, Monday through Friday. In 2015–2016, the operational IVS-R4 network included VLBI stations at Kokee Park (Hawaii), Wettzell (Germany), Ny-Ålesund (Norway), Fortaleza (Brazil), Tsukuba (Japan), Svetloe, Badary and Zelenchukskaya (Russia), Hobart, Katherine, and Yarragadee (Australia), Yebes (Spain), and Matera and Medicina (Italy). A typical R4 consisted of eight to 12 stations. The regular stations for the weekday IVS Intensives were Kokee Park and Wettzell. Intensives including Kokee Park, Wettzell, and Svetloe were occasionally scheduled in order to characterize the Kokee Park to Svetloe baseline so that Svetloe can be used as an alternate for Wettzell should it be needed. The Tsukuba–Wettzell baseline was observed for eight weeks while Kokee Park was undergoing repairs. The Operation Center updated the version of *sked* as updates became available. All sessions are correlated at the Washington Correlator, which is located at USNO and is run by NEOS.

U. S. Naval Observatory

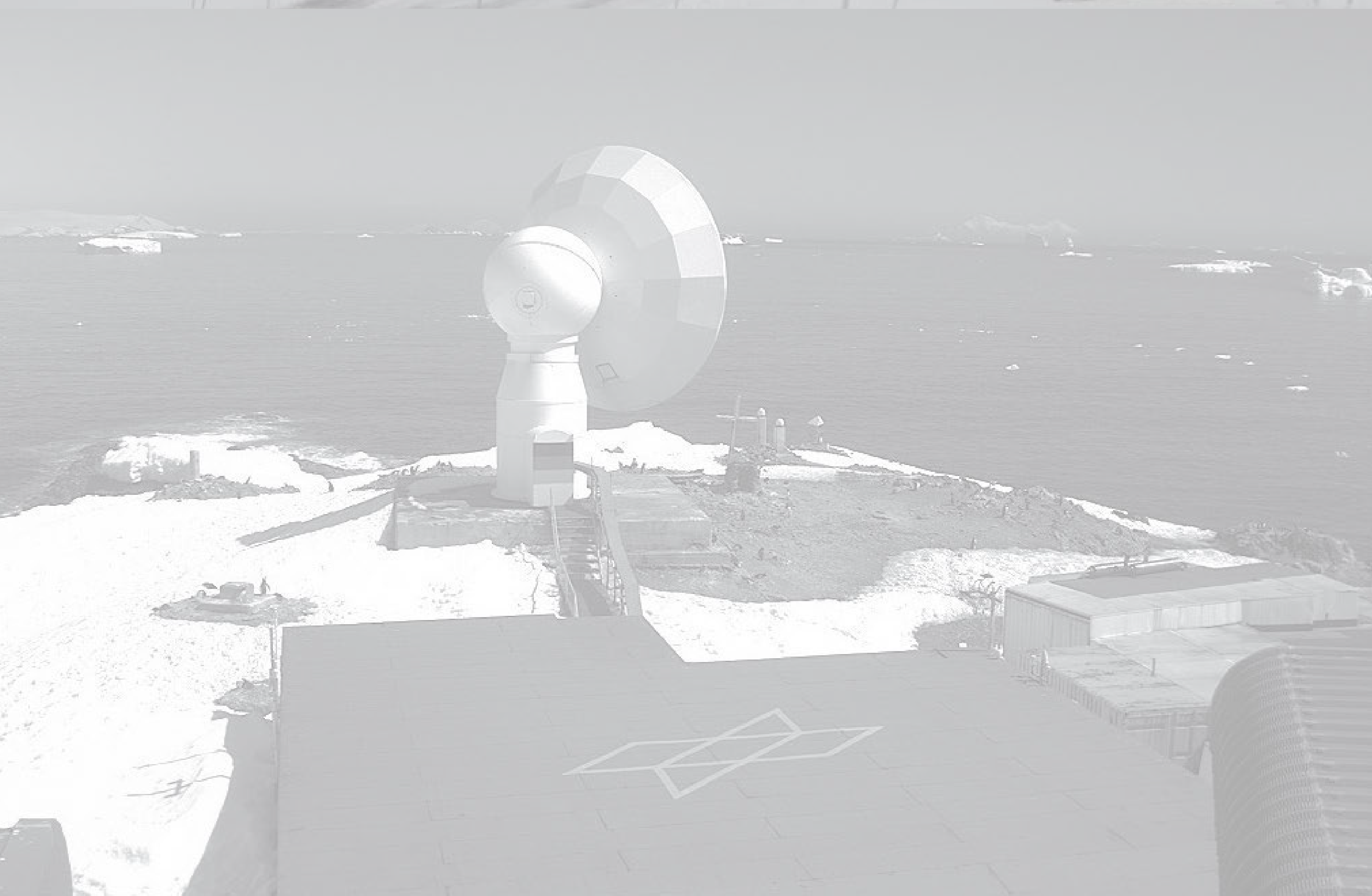
NEOS Operation Center

IVS 2015+2016 Biennial Report

2 Staff

D. M. Hall and M. S. Carter are the only staff members of the NEOS Operation Center. Mr. Hall is responsible for the overall management, and Carter makes the schedules. M. S. Carter is located at the USNO Flagstaff Station (NOFS).

Correlators



The Bonn Astro/Geo Correlator

Alessandra Bertarini [1,2], Walter Alef [2], Simone Bernhard [1], Gabriele Bruni [2], Laura La Porta [1], Arno Müskens [1], Helge Rottmann [2], Alan Roy [2], Gino Tuccari [2,3]

Abstract The Bonn Distributed FX (DiFX) correlator is a software correlator operated jointly by the Max-Planck-Institut für Radioastronomie (MPIfR), the Institut für Geodäsie und Geoinformation der Universität Bonn (IGG), and the Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt, Germany.

1 Introduction

The Bonn correlator is hosted at the MPIfR[1] VLBI correlator center in Bonn, Germany. It is operated jointly by the MPIfR and the BKG[2] in cooperation with the IGG[3]. It is a major correlator for geodetic observations and astronomical projects such as VLBI at millimeter wavelengths, astrometry, RadioAstron[4] VLBI observations, and pulsar VLBI.

1. Institut für Geodäsie und Geoinformation der Universität Bonn
2. Max-Planck-Institut für Radioastronomie
3. Istituto di Radioastronomia - INAF

Bonn Correlator

IVS 2015+2016 Biennial Report

[1] http://www.mpifr-bonn.mpg.de/
[2] http://www.bkg.bund.de/
[3] http://www.gib.uni-bonn.de/
[4] http://www.asc.rssi.ru/radioastron/

2 Present Correlator Capabilities

The DiFX correlator[5] was developed at Swinburne University in Melbourne by Adam Deller and other collaborators. It was adapted to the VLBA operational environment by Walter Brisken and the NRAO staff, and it is constantly updated by the worldwide DiFX developers group. In Bonn, the DiFX is running on a High Performance Compute Cluster (HPC cluster). Its technical specifications can be gathered from the most recent annual report.

Fig. 1 Gabriele, who is checking a Mark 6 unit before its usage.

[5] DiFX: A Software Correlator for Very Long Baseline Interferometry using Multiprocessor Computing Environments, 2007, PASP, 119, 318

3 Staff

The people in the Geodesy VLBI group at the Bonn correlator are:

Arno Müskens - group leader and scheduler of T2, OHIG, EURO, and INT3 sessions.
Simone Bernhart - correlator support scientist and data analyst for geodesy, e-transfer support, Web site maintenance.
Alessandra Bertarini - correlator support scientist and data analyst for both astronomy and geodesy, digital baseband converter (DBBC) testing.
Laura La Porta - correlator support scientist and data analyst for geodesy and near-field VLBI observation, e-transfer support, DBBC testing, software developer.

The people in the astronomical group at the Bonn correlator are:

Walter Alef - head of the VLBI technical department, computers and cluster administrator.
Alan Roy - deputy group leader, APEX project manager, development of linear to circular polarization conversion software for phased ALMA.
Gabriele Bruni - support scientist and data analyst for RadioAstron, e-transfer support.
Sven Dornbusch - FPGA programming for DBBC. APEX.
Heinz Fuchs - correlator operator until the end of 2015 and media shipment.
David Graham - consultant (technical development and DBBC development).
Rolf Märtens - technician maintaining cluster hardware and Mark 5/6 playbacks.
Helge Rottmann - cluster administration and developer for the ALMA phasing project.
Hermann Sturm - correlator operator and software developer.
Gino Tuccari - guest scientist from INAF, DBBC project manager and developer.
Michael Wunderlich - engineer, DBBC development and testing components.

4 Status

Experiments: In the two-year period 2015/16 the Bonn group correlated about 80 R1, twelve EURO, twelve T2, twelve OHIG, 100 INT3 experiments, and astronomical sessions (including 1 mm, 3 mm, RadioAstron and astrometric projects).

e-VLBI: The total disk space available for geodetic e-transfer data storage at the correlator is about 600 TB. On average $\geq$ 90 % of the stations do e-transfer. The average amount of e-transferred data per week is about 20 TB, considering only the regular INT3 and R1 experiments. Since September 2015 every second R1 is now observed at 512 Mbps; hence the increase in data transferred. Most transfers are done either using the UDP-based Tsunami protocol, or the Mark 5A/B/C control software “jive5ab”, which was developed at the Joint Institute for VLBI. Both systems can achieve data rates from 100 Mbps to 800 Mbps. In 2016 the University of Bonn made available an extra 1 Gbps Internet connection to use for e-VLBI transfers; hence now the total capacity toward Bonn is of 2 GB. The upgrade of the line to meet the requirements of VLBI Global Observing System (VGOS) has not been realized yet - still due to funding issues and apparently bureaucratic obstacles.

DiFX software correlator: The DiFX software correlator has been operated in Bonn since 2009 and is updated regularly. Since the second half of 2015 Bonn has a new cluster with more than 1,000 compute cores. In January 2015 the correlator’s playback unit included two Mark 6 recorders, now increased to five units.

The stable DiFX release 2.4 was installed in 2015.

Two other branch versions of the DiFX software correlator are available in Bonn: a DiFX version for RFI mitigation, developed by J. Wagner, now at KASI, and a DiFX version dedicated to RadioAstron, developed by J. Anderson, now at GFZ Potsdam.

DBBC: The Bonn group is involved in the development and testing of the most widely adopted VLBI backend: DBBC2 and its ancillary parts (e.g., FiLa10G) for the European VLBI Network (EVN) and geodesy. The DBBC2 is designed as a full replacement for the existing VLBI terminals and includes additional features. Stations like for instance APEX, Pico Veleta, AuScope (Australia), HartRAO (Africa), and a large part of the EVN have ordered one or more DBBC2s.

The FiLa10G, VLBI to 10GE interfaces have also been exported to Haystack and Korean stations.

The next generation DBBC (DBBC3-L) is being developed and two prototypes are being integrated and tested. The DBBC3-L can handle a larger bandwidth of 4 GHz for each IF/polarization. A maximum of eight IFs can be processed by a single DBBC3-L, so a dedicated variant of the modular system can also be used as complete VGOS backend at 32, 64, 128 Gbps covering the full RF range up to 16 GHz.

APEX: The Bonn VLBI group has equipped the APEX telescope for VLBI observations at 1 mm. In 2013 APEX conducted the first scientific observations by taking part in the Event Horizon Telescope (EHT) campaign. Observations were carried out at 4 Gbps, lasted about 50 hours and provided good detections for several sources including Sgr A* and M87.

RadioAstron: Data from ten global+RadioAstron experiments have been transferred to Bonn during AO-2 and AO-3 observing periods (July 2014–July 2016), plus another four from the ongoing AO-4. The correlation of the three key science projects based in Bonn is regularly proceeding, and since AO-2 also experiments from single PIs are being processed. Eleven experiments were finalized in 2015/2016. Raw data are routinely transferred to ASC (Moscow) via Internet or HDD for backup purposes. The final version of the RadioAstron-dedicated DiFX is in use since September 2016, and also distributed on the official DiFX repository.

5 Outlook for 2017

First prototype for the prime focus for BRoad-baND (BRAND), the new wideband “digital” VLBI-receiver for the EVN, whose frequencies span from 1.5 GHz to 15.5 GHz.

Haystack Observatory VLBI Correlator 2015–2016 Biennial Report

Mike Titus, Roger Cappallo, Brian Corey, Kevin Dudevoir, Arthur Niell, Jason SooHoo, Alan Whitney

Abstract This report summarizes the activities at the Haystack Correlator during 2015–2016.

Fig. 1 Partial view of the Haystack DiFX correlator, showing two racks containing seven computer servers, three file storage servers, one Qlogic infiniband switch, and two Mark 6 playback units.

MIT Haystack Observatory

Haystack Correlator

IVS 2015+2016 Biennial Report

1 Introduction

The DiFX VLBI correlator of the MIT Haystack Observatory, located in Westford, Massachusetts, is supported by the NASA Space Geodesy Program and the National Science Foundation. It is dedicated mainly to the pursuits of the IVS, with a smaller fraction of time allocated to processing radio astronomy observations for the Event Horizon Telescope (EHT) project. The Haystack correlator serves as a development system for testing new correlation modes, such as those needed for the VGOS observations, and for recorder developments, such as the Mark 6 system. Some software support is provided to similar DiFX installations at the U.S. Naval Observatory, to the Max Planck Institute for Radioastronomy in Bonn, Germany, and to the general IVS community for DiFX processing of IVS experiments.

2 Summary of Activities

2.1 VGOS Activities in General (Formerly Referred to as Broadband Delay)

The last two years have marked a significant ramping up of the VGOS project. A regular series of experiments using the GGAO12M–Westford baseline established the attainable accuracy of the technique, then the build-out, testing and commissioning of the Kokee12M antenna expanded the VGOS network to three stations. Interspersed with that, international sites such as the RAEGYEB antenna at Yebes, Spain and the Wettzell South VGOS antenna in Wettzell, Germany joined the

US network in many commissioning tests using IF signal chains of their own design and digital back ends comprised of an amalgam of DBBC2s, ADS3000s, and Haystack-designed RDBEs. A site in Ishioka, Japan also joined in for a smaller number of tests using their own IF signal chain and ADS3000 recorders. All this combined to make a VGOS network of six stations. Regular experiments in the form of a VGT then VGP series comprised of collections of these antennas in various combinations were conducted in order to validate and/or improve performance of the equipment at each of the sites. Much effort has especially been put into diagnosing and fixing various problems seen in the European DBBCs, which have displayed various performance deficiencies. Overall, we are progressing rapidly toward a functioning network but some fundamental problems need to be solved, most notably phase and amplitude stability across the band with the Yebes and Wettzell systems.

2.2 Kokee12M VGOS Commissioning

An extensive series of experiments was conducted in order to test the data acquisition rack, detect initial fringes, and validate the integrity of the signal chain of the newly constructed 12-m antenna built at Kokee Park. The series included zero baseline tests of the data acquisition rack while set up at the Westford site using its signal chain split with Westford, on-site fringe test experiments with GGAO12M and Westford, then complete 24-hour experiments in standard VGOS mode with GGAO12M and Westford. Also, "mixed mode" tie experiments were conducted with the Kokee 20M antenna recording in parallel using traditional S/X mode and the Kokee12M, Westford, or GGAO12M recording in broadband mode. These tests successfully showed the signal chain to be of high quality and equivalent to the extensively tested GGAO12M and Westford signal chains, and tied the position of the new 12-m antenna into the reference frame of the traditional S/X network. An entire series of about 17 experiments devoted to Kokee12m commissioning was conducted.

2.3 Wettzell South, Yebes (RAEGYEB), Ishioka and Kashima VGOS Antenna Commissioning

The Wettzell South and Yebes RAEGYEB antennas began participating in the VGOS experiment series starting in mid-2016. Initial serious problems with the DBBC2 backends were mostly overcome through repeated testing and revision of the DBBC2 firmware and hardware. The Ishioka broadband antenna in Japan also joined for some fringe tests and one 24-hour experiment. The quality of their data was quite good. It should also be noted that in January 2015, a Kashima antenna VGOS signal chain broadband fringe test was conducted and they subsequently joined a VGOS broadband experiment (v15020) for one hour in the highest band; good fringes were found.

2.4 R1 and RD1606 Mixed Mode Tag-along to IVS Experiments

Some combination of GGAO12M and/or Westford tagged along to four IVS S/X R1 sessions namely R1706, R1708, R1716, and R1718 through the second half of 2015 in an effort to develop a "mixed mode" method of tying the traditional S/X stations to the new broadband network. Most recently, Westford tagged along to IVS S/X session RD1606 in mid-July. Much has been learned through these test observations and the process of making them production ready is progressing.

2.5 Mark 6 Real Time Playback

Two methods of playing back data from Mark 6 playback units directly on the correlator were developed over the last two years. Broadband VGOS data sets were provided to the Bonn correlator where, in collaboration with Walter Brisken, they devised a method of directly playing back VGOS format recorded data. Some further development work continued at Haystack in order to fix some bugs, and now this method is used to play back all VGOS data in production mode.

An entirely different real time playback system was developed at Haystack by Geoff Crew and that method has been used extensively for EHT cluster processing. It has also been adapted and used by the Bonn correlator for their portion of EHT processing.

Mark 6 is thus now fully integrated into the production processing system.

2.6 Fourphase Development

A program designed to automate the tedious task of determining X/Y delay and phase offsets needed in order to combine the polarizations of broadband VGOS data has been under development for some time and is now in its testing phase.

2.7 Mark 5B Directory and Data Readback Fixes

Various problems were encountered over the last two years related to reading directories and data from Mark 5B modules. An iterative exchange with Walter Brisken has addressed all of them, although some issues still crop up intermittently.

2.8 64 Channel Processing Development

A method of processing simultaneously all 64 channels in a full broadband VGOS recording was developed by Roger Cappallo in 2015. This was essential to efficient production processing of VGOS broadband data.

2.9 nuSolve Install

The Goddard "nuSolve" package, including database making tools such as vgosDbMake, was installed by Tim Morin. It is now used to generate all databases for VGOS correlated experiments.

2.10 DiFX Software Support

Support for the community continues for difx2mark4, fourfit, and HOPS. This support includes addition of features requested by users, other enhancements, and bug fixes.

2.11 DiFX Cluster Developments

Some upgrades to the "geodetic cluster" were made. The geodetic cluster moved to a new master node and more storage space for e-VLBI was installed. An entirely new cluster built for the purpose of processing large number of stations and future 64 Gb/sec recordings has been constructed by the EHT project, is in routine use and is set to be greatly expanded.

2.12 CorrelX Development

An entirely new software correlator was developed by Antonio Vazquez under the auspices of the Astro and Geoinformatics group led by Victor Pankratius. This work is soon to be released to the public.

2.13 Haystack 37 Meter Antenna Recommissioning

Re-commissioning of the rebuilt Haystack 37-meter antenna for VLBI observations was conducted in the second half of 2016. Fringe tests were performed with the VLBA array at 3-mm and 7-mm wavelengths and good fringes were found in both bands.

2.14 e-VLBI

Non-real-time transfers have continued. Data from 29 sessions were transferred to Haystack during the past two years from 16 stations: five in Japan (Ishioka, Kashima34, Kashima11, Koganei, and Tsukuba), four in Western Europe (Onsala, Ny-Ålesund, Yebes, and Wettzell), three in Australia (Hobart, Yarragadee, and

Katherine), one in South America (Fortaleza), two in South Africa (Hart15M and HartRAO) and one in China (Tianma65).

3 Experiments Correlated

In 2015–2016, 87 geodetic VLBI sessions were processed, at least in part, consisting of 16 R&Ds, six T2s, and 65 VGOS-related sessions that were either broadband, mixed mode, or tests of other types, some of which were touched on in the summary above. As usual, smaller tests were not included in the above count because they were too small to warrant individual experiment numbers. All production and test experiments were done on the DiFX cluster.

4 Current/Future Hardware and Capabilities

The geodetic DiFX cluster currently consists of six PCs, each with dual hex core 2.66 GHz Intel Xeon processors. Three file storage servers, which can also act as DiFX compute nodes, provide >200 TB of file storage. These are all connected through a 40 Gb/sec infiniband network fabric using a Qlogic switch. Six Mark 5B and two Mark 6 playback units with DiFX fully installed are connected to the infiniband fabric.

An entirely new EHT cluster consisting of 16 PCs, each with single decacore 2.8 GHz Intel Xeon processors, two equivalent master nodes, and seven Mark 6 playback units, along with 197 TB of data storage space connected through a 40 Gb Ethernet network fabric was constructed and is in operational use since mid-2016. This cluster is mostly dedicated to Galactic Center observations of the EHT, but was also used to process some VGOS broadband experiments. This cluster is set to more than double in compute power and playback unit number in early 2017. The infrastructure is already installed for the new equipment and it is purchased and on its way.

5 Staff

Staff who participated in aspects of DiFX, Mark 5/6, and e-VLBI development and operations include:

5.1 Software Development Team

- John Barrett - software development/support
- Roger Cappallo - post processing; Mark 5B & 6; correlator software integration and troubleshooting; DiFX correlator development
- Geoff Crew - DiFX correlator development, post processing software; Mark 6
- Kevin Dudevoir - correlation; maintenance/support; Mark 5A/5B/5C; e-VLBI; computer system support/development; DiFX correlator development
- Tim Morin - cluster installation/development/maintenance and s/w support
- Jason SooHoo - cluster installation/development/ maintenance and s/w support, e-VLBI; Mark 5A/5B/5C/6
- Jon Rose - cluster installation/development/maintenance and s/w support
- Chester Ruszczyk - e-VLBI; Mark 5A/5B/5C/6
- Alan Whitney - system architecture; Mark 5A/5B/5C/6; e-VLBI

5.2 Operations Team

- Peter Bolis - correlator maintenance
- Alex Burns - playback drive maintenance; Mark 5/6 installation and maintenance; general technical support
- Brian Corey - experiment correlation oversight; station evaluation; technique development
- Morgan Goodrich - general technical support
- Glenn Millson - correlator operator
- Arthur Niell - technique development
- Don Sousa - correlator operator; experiment setup; module library and shipping
- Mike Titus - correlator operations oversight; experiment setup; computer services; software & hardware testing

- Ken Wilson - correlator maintenance; playback drive maintenance; general technical support

6 Conclusion/Outlook

Build-out, commissioning, and expansion of the VGOS broadband network will continue. Standardization and automation of procedures in order to export broadband VGOS processing to other correlators will proceed. Mixed mode observation/correlation methods will be developed and exported. Routine geodetic processing continues as well.

IAA Correlator Center Biennial Report 2015+2016

Igor Surkis, Voytsekh Ken, Yana Kurdubova, Alexey Melnikov, Vladimir Mishin, Nadezhda Mishina, Violet Shantyr, Dmitry Zhuravov, Vladimir Zimovsky

Abstract The IAA Correlator Center activities in 2015 and 2016 are described. All regular observations of Russian national geodetic VLBI programs were transferred to the IAA in e-VLBI mode and correlated using the ARC, RASFX, and DiFX correlators.

1 General Information

The IAA Correlator Center is located at St. Petersburg, Russia and maintained by the Institute of Applied Astronomy. The main goal of the IAA Correlator Center is processing geodetic, astrometric, and astrophysical observations made with the Russian national VLBI network Quasar. At present, three correlators are involved in this processing: ARC, RASFX, and DiFX.

The ARC (Astrometric Radiointerferometric Correlator) is the main data processing instrument in the IAA Correlator Center for UT and EOP determination. The ARC is a six-station 15-baseline correlator. It is able to process up to 16 frequency channels on each baseline for a total of 240 channels. The correlator is able to handle two-bit VLBI signals with 32 MHz maximum clock frequency. The maximum data rate from each station is 1 Gbit per second. The correlator is using VSI-H input signals, and it is equipped with Mark 5B playback systems. The ARC was designed and built by the IAA RAS in 2007–2009. The correlator is the XF type and based on FPGA technology.

The Institute of Applied Astronomy of the Russian Academy of Sciences (IAA RAS)

IAA Correlator Center

IVS 2015+2016 Biennial Report

In 2014, the Russian Academy of Sciences' FX (RASFX) six-station near-real time GPU-based VGOS correlator was developed [1]. The correlator software is installed on an HPC cluster, which contains 40 servers, each equipped with two Intel CPUs and two Nvidia GPUs.

Since 2015, the DiFX software correlator has been installed on the HPC cluster.

2 Activities during the Past Years

ARC commonly operates with data obtained from 32-m antennas, which are located in "Svetloe", "Badary" and "Zelenchukskaya". ARC processes daily Intensive one-hour sessions for UT determination and weekly 24-hour sessions for EOP determination in standard legacy IVS geodetic setup (1-bit, 14 freq. channels of 8 MHz bandwidth). More than 800 sessions were processed in 2015–2016.

In March 2015, RASFX and DiFX correlators were used for comissioning of the new 13-m antennas "Zelenchukskaya" and "Badary" as two element radiointerferometers. Since Novemeber 2015, IAA carried out multiple (up to seven) sessions per day.

In 2015–2016 the following types of sessions were perfomed:

- 0.5-1 hour geodetic program in S/X band for UT determination ("R", two 13-m stations)
- 23-hour geodetic program in S/X band to improve positions for 13-m antennas ("Ru-TEST", two 13-m and three 32-m radio telescopes)
- Test geodetic programs in X/Ka and S/X/Ka bands ("Ru-TEST").

- Miscellaneous test sessions, including international cooperation (“Ru-TEST”).

More than 1,700 sessions were carried out during 2015–2016 [2]. The broadband acquisition system (BRAS) and data transfering and recording system (DTRS), developed in the IAA, were used in e-VLBI mode in all sessions at 13-m antennas [3, 4]. During the sessions 2-8 frequency channels of 512 MHz bandwidth and 2-bit sampling (4-16 Gbps per station) were recorded in VDIF data format.

The RASFX correlator was used for processing for all sessions observed by 13-m antennas; the DiFX correlator was used for correlating all of these sessions.

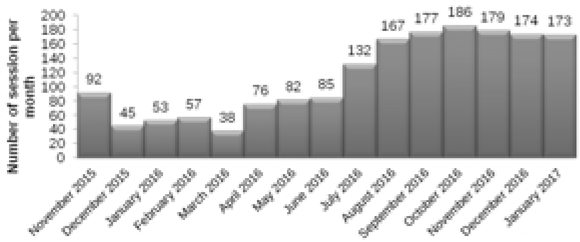


Fig. 1 Monthly distribution of number of sessions.

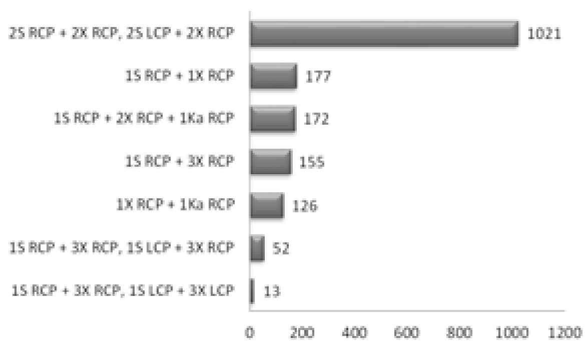


Fig. 2 Distribution of sessions by observational setup.

3 Staff

The list of the staff members of the IAA Correlator Center in 2015–2016 is given below.

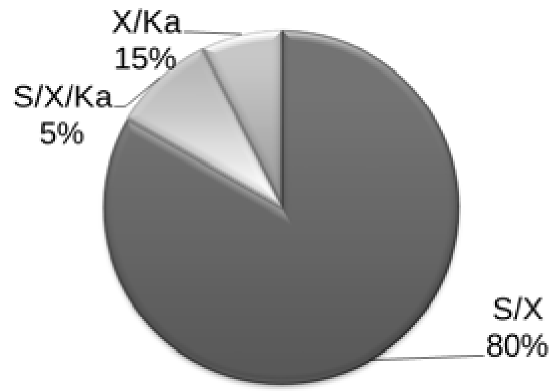


Fig. 3 Distribution of sessions by frequency bands.

- Igor Surkis — leading investigator, software developer;
- Voytsekh Ken — GPU software developer;
- Alexey Melnikov — DiFX processing, scheduler of the Ru-sessions;
- Vladimir Mishin — software developer, data processing;
- Nadezhda Mishina — software developer;
- Yana Kurdubova — software developer, data processing;
- Violet Shantyr — software developer, post processing;
- Vladimir Zimovsky — lead for data processing;
- Ekaterina Medvedeva — data processing;
- Alexander Salnikov — lead for e-VLBI data transfer;
- Ilya Bezrukov — e-VLBI data transfer; and
- Vladislav Yakovlev — e-VLBI data transfer.

4 Future Plans

In 2017 and 2018, the IAA Correlator Center activities will be focused on the following aspects:

- Routine processing of the geodetic observations,
- Processing for improving antenna positions, and
- Developing new features for the RASFX correlator.

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NICT Correlation Center 2015–2016 Biennial Report

Mamoru Sekido, Kazuhiro Takefuji, Masanori Tsutsumi

Abstract This report describes the NICT Correlation Center and its activities.

1 General Information

The VLBI Correlation Center of NICT is operated by Space-Time Standards Laboratory of NICT/Applied Electromagnetic Research Institute and located in the Kashima Space Technology Center. Development of broadband VLBI technology for application to precise frequency comparison of atomic clocks is the primary mission of our group. VLBI experiments for this project have been conducted and processed.

2 Component Description

The VLBI system 'GALA-V' is a broadband VLBI system composed of two small diameter antennas and the Kashima 34-m diameter VLBI station. Upgrading the receiver system [1] and developing a wideband bandwidth synthesis technique [2] have been conducted using these stations. Small (1.6-m and 2.4-m) diameter stations have been installed at the headquarters (HQ) of NICT in Tokyo and the National Metrology Institute of Japan (NMIJ) in Tsukuba, respectively. Both institutes are in charge of keeping time standards UTC(NICT) and UTC(NMIJ) for Japan standard time (JST) and for metrology. A series of VLBI experiments for clock comparison have been conducted in 2016 between UTC(NICT) and UTC(NMIJ) [3]. This NICT–NMIJ baseline is used as a good testbed for broadband VLBI system development for clock comparison applications.

Fig. 1 Correlators of NICT/Kashima using the GICO3 software correlator.

The data acquisition mode used in the GALA-V observing is 2048 Msps/1bit/4ch. The total data rate is 8192 Mbps per station.

The correlation of the Kashima–Koganei and Kashima–Tsukuba baselines is performed for each of the four channels with the GICO3 software correlator [4]. Figure 1 shows the look of the correlation system with the GICO3 correlation system. Computer specification of the cluster computers for correlation is summarized in Table 1.

About 30 TB of data is acquired per day per station. One session of the GALA-V project continues for two to three days. Currently, observed data is collected by physical transportation of the disk set for the Tsukuba

Kashima Space Technology Center, National Institute of Information and Communications Technology

NICT Correlation Center

IVS 2015+2016 Biennial Report

Table 1 Specifications of computers used for correlation at the NICT/Kashima Correlation Center.

Machine	CPU	Memory	RAID
A	Intel i7-3960x v2 6-Core 3.3GHz	64 GB	
B	Xeon E5-2680 v2 20Core 2.8GHz (Dual CPU)	64 GB	Areca ARC-1882ix-24
C	Xeon E5-2680 v2 20Core 2.8GHz (Dual CPU)	64 GB	Areca ARC-1883ix-24
D	Xeon E5-2687 v2 16Core 3.4GHz (Dual CPU)	64 GB	Areca ARC-1882ix-24

NMIJ station. Data recorded at the Koganei-HQ station is shared over a 10-Gbps network between Kashima and Koganei in collaboration with research testbed network JGN. The data processing takes one to two times the data acquisition rate. Thus, it takes a few days to correlate about a total of 150 TB of observation data.

3 Staff

Members who are contributing to the Correlation Center of NICT are listed below (in alphabetical order):

- KONDO Tetsuro: Development of wideband bandwidth synthesis software for the GALA-V project.
- SEKIDO Mamoru: Coordination of VLBI observing and data analysis with CALC/SOLVE.
- TAKEFUJI Kazuhiro: Operating the correlator to process broadband data.
- TSUTSUMI Masanori: Maintaining the computer server of the K6 VLBI recording system and the correlation cluster computers.

4 Activities

4.1 Application of High Time Resolution Output of GICO3

Recently, we adopted the high time resolution output of GICO3 for data processing of the Giant Radio Pulse (GRP) from the Crab pulsar [5]. When we process normal VLBI data with a digital FX-type correlator, data integration after Fourier transformation and multiplication are applied to improve the signal-to-noise ratio of the cross-spectrum. However, in the case of time varying radio signals such as giant radio pulses and fast radio bursts, which have instantaneous frequency characteristics, integration of a signal smears its signal characteristics. To avoid the smearing of a temporal radio signal, the high time resolution data output mode of the GICO3 software correlator was used for processing GRP signals observed from the Crab pulsar. Figure 2 shows the dynamic cross-spectrum of the GRP that arrived from the Crab pulsar and was observed by the Usuda 64-m and Kashima 34-m baseline. The curved line in the figure indicates a strong single GRP affected by frequency dependent dispersive delay. In total, 22,000 (50 ms / 16 μs $\times$ seven 32 MHz bandwidths) data points are included in the figure.

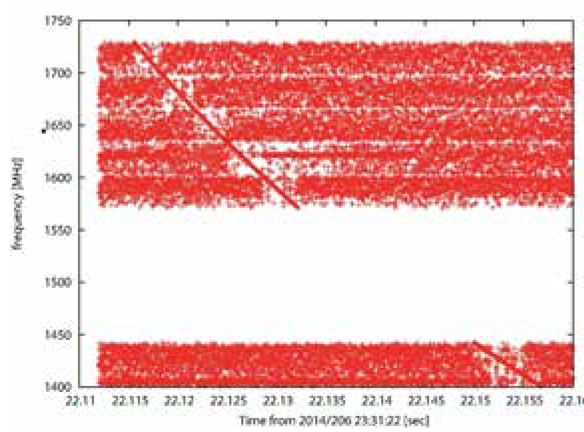

Fig. 2 Dynamic cross-spectrum of a Giant Radio Pulse from the Crab pulsar. A strong giant pulse from the Crab pulsar was detected by correlation of VLBI data between the Kashima 34-m and Usuda 64-m stations at 23:31:22 UT on 26 July 2014. Each point in the figure indicates signals exceeding a certain threshold in the cross-spectra obtained at every 16 μs. The empty frequency range around 1450–1550 MHz is out of the receiver range, because this range is excluded by the superconductor filter in front of the LNA to eliminate RFI from a cell phone base station.

4.2 Development of Cross-Correlation Spectrometry: XCS

We have developed a new method of data processing for radio telescope observation data to measure

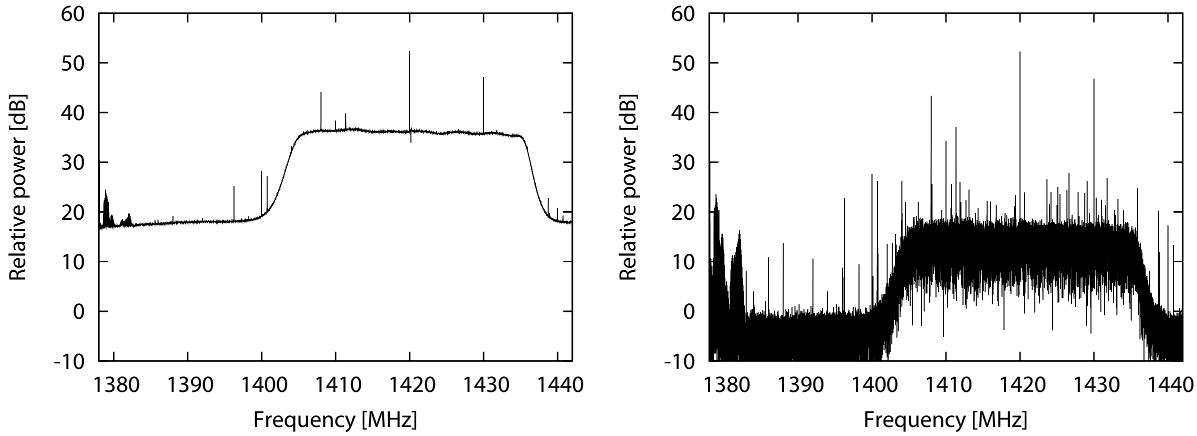

Fig. 3 Band profile of the Kashima 34-m station's L-band by general spectrometry (left). The same data processed by XCS processing (right). Some spurious signals with temporal coherence were enhanced.

time-dependent temporal coherence; we call it cross-correlation spectrometry (XCS) [6]. The XCS is an autocorrelation procedure that expands time lags over the integration time and is applied to data obtained from a single-dish observation. The temporal coherence property of received signals is enhanced by XCS. Figure 3 shows a bandpass profile of the Kashima 34-m station's L-band (1405 to 1435 MHz) processed by general spectrometry (left) and XCS (right), respectively. The XCS processed result shows that random noise is reduced and that some spurious signals with temporal coherence are enhanced.

Acknowledgements

Sharing of VLBI data for correlation of the Kashima–Koganei baseline is realized via a 10-Gbps network supported by high speed research testbed network JGN[1].

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Shanghai VLBI Correlator

Fengchun Shu [1,2], Wu Jiang [1], Zhong Chen [1,2], Juan Zhang [1], Weimin Zheng [1,2]

Abstract This report summarizes the activities of the Shanghai VLBI Correlator during 2015 and 2016. Highlights include the intensive and reliable DiFX operation, growing e-VLBI connection with international stations, conversion of the CVN correlator output to the Mark IV file system, fringe tests for Tianma65, and running PIMA analysis.

1 Introduction

The Shanghai VLBI Correlator is hosted and operated by the Shanghai Astronomical Observatory (SHAO), at the Chinese Academy of Sciences (CAS). It is located at the Sheshan campus, about 40 kilometers from the Xujiahui headquarters of SHAO. The Shanghai correlator plays a leading role in the data processing of the Chinese VLBI Network (CVN), inclusive of the CMONOC project for monitoring the Chinese regional crustal movement and the Chinese deep space exploration project for spacecraft tracking.

As shown in Figure 1, Shanghai (including Seshan25 and Tianma65), Kunming, and Urumqi participate in some domestic geodetic and astronomical sessions, while the Beijing station is mainly used for spacecraft data downlink and VLBI tracking. A few joint observations with the Chinese deep space stations Kashi and Jiamus were also performed.

1. Shanghai Astronomical Observatory, Chinese Academy of Sciences
2. Key Laboratory of Radio Astronomy, Chinese Academy of Sciences

Shanghai Correlator

IVS 2015+2016 Biennial Report

The Shanghai correlator was accepted as an IVS correlator in March 2012. It began to correlate the IVS data using the DiFX in 2015. In the long run, our goal is to correlate a weekly IVS observing session on a regular basis.

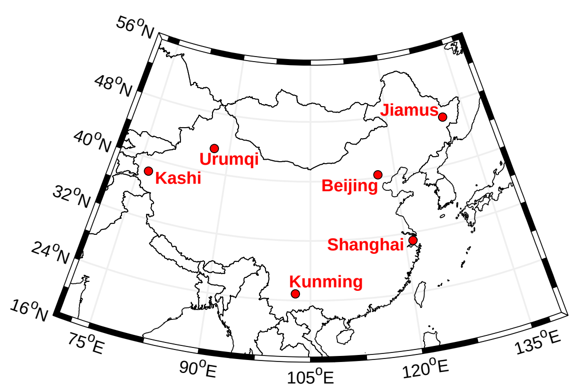

Fig. 1 Distribution of the VLBI stations in China.

2 Component Description

We are operating two types of correlators. The CVN correlator developed by our own staff has been operational since 2006. It is mainly used for spacecraft VLBI tracking in the Chang'E lunar exploration project by producing differential VLBI observables. The data latency is less than one minute in real time mode, and the typical accuracy is better than 1 ns. It has also been used to correlate a few tens of CMONOC geodetic sessions before 2014. The other one is the DiFX software correlator, which is dedicated to astrophysical and geodetic data correlation.

The DiFX software was installed on a powerful hardware platform in December 2014, with a 420 core cluster system and a 430 TB storage space, as shown in Figure 2. This new platform is very important for the IVS data correlation. In the routine operations, half of the computing and the storage sources are assigned to the geodetic correlation tasks. Features of the DiFX cluster system are listed as follows:

- DiFX 2.2/2.3/2.4/trunk, HOPS 3.9/3.10/3.11/3.12
- Head nodes: DELL R820 (E5-4610 CPU, 2.4 GHz, 2*6 cores), 64 GB Memory, DELL R730 (E5-2623 CPU, 3.0 GHz, 2*4 cores), 64 GB Memory.
- Computing nodes: 20 DELL R630 nodes, two socket Intel E5-2660 CPU (2.6 GHz, ten cores), 64 GB Memory, 400 cores in total
- I/O nodes: RAID6, 432 TB raw storage capacity
- Mark 5 units: three Mark 5A and three Mark 5B.
- 56 G Infiniband for internal computing network connection
- 1/10 G Ethernet for internal and external network connection

Fig. 2 DiFX cluster system and Mark 5A/B units.

3 Staff

The people involved in the operation and development of the Shanghai Correlator are listed below.

- Weimin Zheng: group head, software correlator, and VLBI terminal development
- Xiuzhong Zhang: CDAS and other technique development
- Fengchun Shu: scheduler, experiment oversight, and CDAS evaluation
- Zhong Chen: e-VLBI and cluster administration
- Wu Jiang: DiFX operation and experiment support
- Tianyu Jiang: DiFX operation and experiment support
- Wenbin Wang: media library and experiment support
- Zhanghu Chu: operator and experiment support
- Renjie Zhu: CDAS development
- Zhijun Xu: FPGA programming and hardware correlator development
- Juan Zhang: software correlator development and maintenance
- Li Tong: software correlator development and maintenance
- Lei Liu: post-doctoral fellow and software correlator development

4 Summary of Activities

4.1 DiFX Correlation

For regular IVS data correlation, we use the DiFX, HOPS, and Dbedit software to generate Mark III database files and submit them to the IVS Data Center, in a similar way that the other IVS correlators do.

In order to make the correlation results reliable, we made comparisons with the Bonn correlator of the CRF86 and CRF87 sessions in 2015 and the K16095 session in 2016. Although the two correlators used different parameter configurations, the total delay observables can be used for comparisons. The results show that the WRMS of group delay differences is less than 2 ps at X-band and less than 8 ps at S-band, far below the measurement thermal noises.

4.2 e-VLBI

The network link to Seshan25 and Tianma65 is 10 Gbps. The network link to the Urumqi, Kunming, and Beijing stations is 155 Mbps for domestic e-VLBI observations. For the future Chang'e 5 lunar mission, we have planned to make data transfer at a 128 Mbps data rate for each station.

In order to process IVS global sessions, we have established the network link to most of the IVS stations, the Bonn correlator, and the Haystack correlator as well. The maximum data rate is 1 Gbps. All international stations except Kokee e-transfer data to Shanghai.

4.3 Development of the CVN Software Correlator

We implemented offline software, *cvn2mk4*, which can convert the CVN correlator output to the Mark IV file system, so that the correlation results could be processed by HOPS. Other offline software, *cvn2fits*, can make the CVN correlator output to be loaded into the AIPS for imaging.

In 2016, we processed the K14349 and cn1502 sessions with the CVN software correlator and the DiFX respectively. Then the correlator output was processed by the HOPS. Comparisons were made of the SNR, group delay, and delay rate. The results indicated that the group delay and rate observables agree well, while the SNRs produced from the CVN correlator are slightly less than those from the DiFX correlator. The comparison of SNR differences for K14349 is shown in Figure 3.

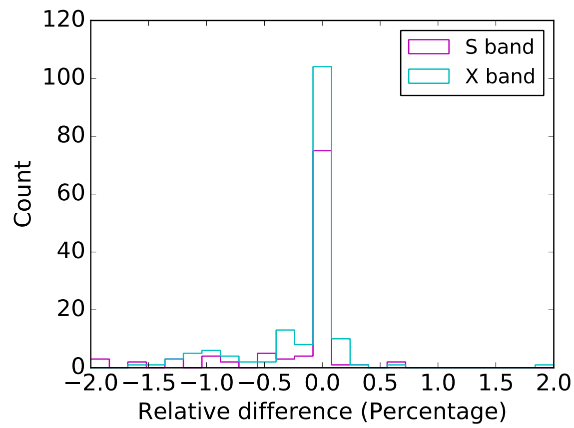

Fig. 3 Histogram of the relative SNR difference of the CVN correlator with repect to the DiFX correlator in K14349.

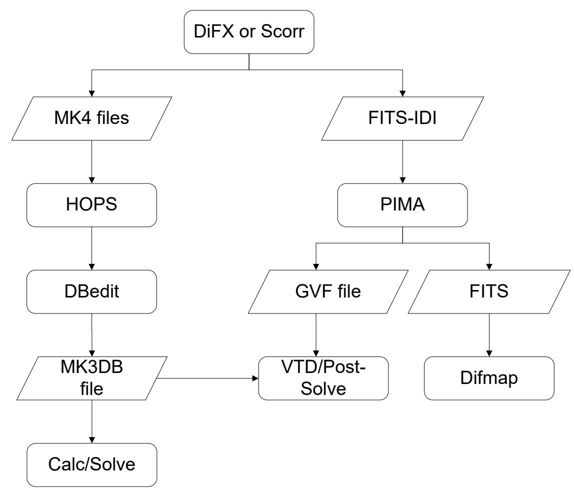

Fig. 4 Data flowchart based on the HOPS and PIMA software.

4.4 Running PIMA Analysis

The VLBI post-correlation analysis software PIMA was developed in recent years, aimed at absolute astrometry and radio imaging with high efficiency and weak fringe detection. We installed the PIMA in 2015, which performs phase calibration, complex bandpass calibration, and fringe search with advanced methods.

For some VLBI experiments correlated at SHAO, such as APSG, AOV, and VEPS sessions, we generated FITS-IDI formatted data and ran PIMA analysis regularly. Figure 4 shows the data flowchart based on the HOPS and PIMA software.

4.5 VEPS

We conducted 13 24-hour VEPS (VLBI Ecliptic Plane Survey) sessions in the search mode. Seshan25, Kunming, and Urumqi are core participating stations, while Kashim34, Hobart26, and Sejong took part in the observations on an ad hoc basis. The data volume for each station is approximately 16 TB, eight times bigger than that recorded in regular IVS geodetic sessions, so the data correlation of one VEPS session usually took more than 24 hours.

4.6 Experiments Correlated

Within the framework of the IVS, we correlated 11 sessions in 2015 and 28 sessions in 2016. We also organized a few Chinese domestic geodetic VLBI experiments and some VEPS observations. More details can be found in Table 1.

Table 1 Statistics of experiments correlated.

Session Name	2015	2016
AOV	3	3
APSG	2	2
AUS-AST	0	7
AUS-GEO	0	6
IVS-CRF	6	6
IVS-CRDS	0	3
IVS-R&D	0	1
CN-GEO	5	4
VEPS	6	7

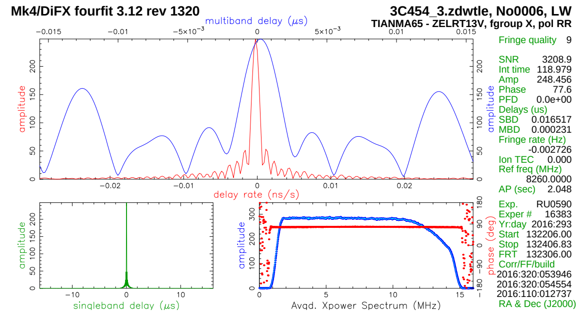

Fig. 5 X-band fringes on the baseline Tianma65-Zelen13m.

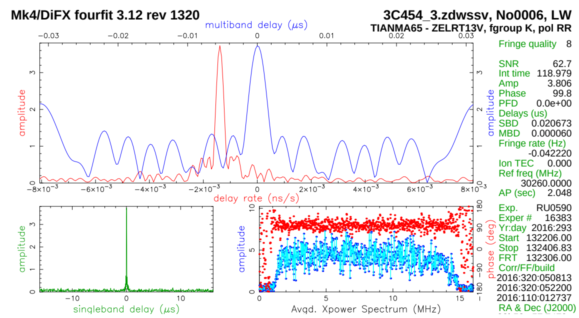

Fig. 6 Ka-band fringes on the baseline Tianma65-Zelen13m.

4.7 Fringe Tests for Tianma65

We conducted an X/Ka-band fringe test with Tianma65, Badar13m, Zelen13m, and Wettz13n on October 28, 2015. Fringes to Tianma65 were found at Ka-band but not X-band. After a few more fringe tests on the baseline Tianma65-Seshan25, we conducted another X/Ka-band fringe test with Tianma65, Badar13m, and Zelen13m on October 19, 2016. Tianma65 used the standard GEO mode, i.e., ten IF channels spread over Ka-band and six IF channels spead over X-band. The bandwidth per IF channel is 16 MHz. The Russian stations used two IFs with 512 MHz bandwidth each, recorded in VDIF format. We made correlations with the DiFX zoom band mode. Fringes to Tianma65 were obtained at X/Ka dual band for the first time, as shown in Figure 5 and Figure 6.

4.8 DiFX Meeting

The 10th DiFX Users and Developers Meeting was held in Shanghai, October 30 – November 3, 2016. More than 20 participants from nine countries and regions were hosted by our correlator operation team (Figure 7). There were 21 oral talks presented at the users meeting, which was arranged for the first two days. Then the developers worked together in the next three days for planning the DiFX updates. During the meeting, an excursion was arranged to visit the Shanghai correlator located at the Sheshan campus and the Tianma Radio Telescope.

Fig. 7 Participants of the 10th DiFX Users and Developers Meeting.

5 Future Plans

We plan to correlate 31 observing sessions assigned by the IVS in 2017. To ensure that the final results are reliable and convincing, we plan to make comparisons with other IVS correlators, focused on the use of multi-tone phase calibration. We will continue to support the data correlation of the Chinese domestic VLBI observations with a growing number of experiments and stations.

We will continue to develop the CVN software correlator in order to use it to process some geodetic experiments. Construction of the Seshan VGOS station is scheduled to be finished in 2017. It will be challenging to obtain real VGOS data for trial correlation.

Acknowledgements

We are very grateful to Alessandra Bertarini for commissioning our DiFX operation. We also acknowledge the National Natural Science Foundation of China (NSFC) for funding projects VEPS (U1331205) and BBD measurement (11573056).

Tsukuba VLBI Correlator

Takahiro Wakasugi [1], Tetsuya Hara [1,2]

Abstract This report summarizes the activities of the Tsukuba VLBI Correlator during 2015 and 2016. The weekend IVS Intensive (INT-2) sessions and the Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) sessions were regularly processed using the K5/VSSP correlation software. In addition, the Japanese domestic VLBI observations (JADE) were also correlated in 2015.

1 Introduction

The Tsukuba VLBI Correlator, located in Tsukuba, Japan, is operated by the Geospatial Information Authority of Japan (GSI). It is fully devoted to processing geodetic VLBI observations of the International VLBI Service for Geodesy and Astrometry (IVS). All of the weekend IVS Intensive (INT-2) sessions for UT1-UTC (= dUT1) determination and the Japanese domestic VLBI observations for geodesy called JADE organized by GSI were processed at the Tsukuba VLBI Correlator. Moreover, half of the Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) sessions, which started as regular sessions in 2015, were also correlated. The K5/VSSP correlation software developed by the National Institute of Information and Communications Technology (NICT) is used for all processing.

1. Geospatial Information Authority of Japan
2. Advanced Engineering Service Co., Ltd.

Tsukuba VLBI Correlator

IVS 2015+2016 Biennial Report

2 Component Description

2.1 e-VLBI

The Tsukuba VLBI Correlator has been connected to a broadband network, and all of the observed VLBI data are delivered via the network. The Tsukuba VLBI Correlator has a 10-Gbps dedicated link to the SINET5 operated by the National Institute of Informatics (NII), which is connected to several research networks in the world such as Internet2 in the U.S., GÉANT2 in Europe, and TEIN4 at Singapore. It enabled us to transfer a massive amount of data between the Tsukuba VLBI Correlator and the overseas IVS Components. The Ishioka VGOS Station has also been connected to the Tsukuba VLBI Correlator and SINET5 with a 10-Gbps dedicated cable since 2014.

2.2 K5/VSSP Correlation Software

The K5/VSSP correlation software consists of several programs for the calculation of a priori values of delay and delay rate (*apri_calc*), for the correlation processing for all observations (*fx_cor or cor*), and for monitoring the results of the correlation processing by performing a so-called "coarse search" (*sdelay*), followed by several utilities such as *Komb* for bandwidth synthesis [1]. All of these programs were developed and have been maintained by NICT. The K5/VSSP correlation software can be used not only for K5 data processing but also for Mark 5 data processing by using the data format conversion program (*m5tok5*).

Table 1 Correlator hardware capabilities.

	Main system	**Backup System**
Number of servers	16 - 14 for correlation processing - 2 for controlling correlation processing	44 - 16 for correlation processing - 2 for controlling correlation processing - 26 for data storage
Operating System	Red Hat Enterprise Linux 6.3	CentOS version 5.5
CPU	Intel Xeon X5687 @3.60GHz quad CPU x 2	Intel Xeon X3360 @2.83 GHz quad CPU Intel Xeon 5160 @3.00 GHz dual CPU x 2 Intel Xeon X3480 @3.07 GHz quad CPU Intel Xeon @3.80 GHz CPU x 2
Total storage capacity	Data Direct Networks storage: 513 Tbytes	Lustre File System: 30 Tbytes
Network	10 Gbps dedicated line connected to SINET5 by NII	

The following are processes of the K5 correlation and programs used in each process.

1. Transferring data from network stations to the correlator (*tsunami and tsunamid*, or *jive5ab*).
2. Data format conversion from Mark 5 to K5 (*m5tok5 or m5btok5*).
3. Preparation of a priori parameter files (*apri_calc*).
4. Fringe search to find a clock offset at each pair of stations (*fx_cor or cor*).
5. Running correlation processing for all observations (*fx_cor or cor*).
6. Coarse search for estimating residual delays and delay rates, then plotting these values on a 3-D diagram (*sdelay*).
7. Bandwidth synthesis to derive multi-band delays (*komb*), then the creation, by *MK3TOOLS*, of Mark III databases to be submitted to the IVS Data Centers.

The correlation and analysis management programs developed by GSI can run the above processes consecutively and ultra-rapidly. The program for the management of data transfer *rapid_transfer* accesses a data server in an observing station, executes *tsunamid* there, and then executes *tsunami* to transfer data automatically at the correlator side when an observation starts. The data is converted from Mark 5 to K5 format by a program *rapid_conv* as necessary. *Rapid_cor* is a program that performs a fringe search for each baseline according to the clock information of each station written in the FS log. Once the fringe is detected, the main correlation processing is run sequentially with the clock offset and rate found in the fringe search until the last observation. *Rapid_komb* executes successive runs of *komb* for bandwidth synthesis processing. The fully automated VLBI analysis software *c5++* developed by NICT can read the komb output files directly and derives a VLBI solution [2]. *Rapid_c5pp*, which provides an interface for *c5++*, makes a configuration file for *c5++* automatically and executes analysis.

2.3 Correlator Hardware Capabilities

The hardware supporting the activities of the Tsukuba VLBI Correlator is summarized in Table 1. All of these pieces of equipment are general purpose and commercially available products. It means that no dedicated hardware is required in the K5 correlation processing. In 2014, IBM System X3650 servers and a Data Direct Networks storage system with a capacity of 513 TB were incorporated into the main correlation processing (Figure 1). It shortens the time of processing of correlation by about half. The existing system is also available as a backup system (Figure 2).

3 Staff

The technical staff at the Tsukuba VLBI Correlator are:

- **Takahiro Wakasugi** — correlator/analysis chief, management.
- **Tetsuya Hara** (AES) — correlator/analysis operator, software development.

Fig. 1 View of the main system (data processing servers and storage) at the Tsukuba VLBI Correlator.

4 Correlator Operations

4.1 IVS Intensive for UT1-UTC

In total, 104 and 115 Intensive sessions that were observed on weekends were processed at the Tsukuba Correlator in 2015 and 2016, respectively. The details are described in Table 2. The observed data at Wettzell are transferred to the Tsukuba Correlator in near real-time with the Tsunami UDP protocol and are converted to the K5 format immediately. The observed data at the Tsukuba station are also transferred to the correlator at once. The whole process from data transfer through analysis is implemented by the *rapid_* programs (see Section 2.2), and a dUT1 solution of the Tsukuba–Wettzell baseline can be derived within a few minutes after the end of the last scan of the session. In addition, we started the Ishioka–Wettzell baseline observations called Q-Intensive from October 2016 in order to validate dUT1 solutions with the new baseline. We confirmed that all of the processes were working well for Ishioka with a slight modification.

Table 2 Intensive sessions processed at the Tsukuba Correlator.

2015	Baseline	Period	# of sessions
Intensive 2	TsWz	Jan 03 – Dec 27	99
	KbWz	Oct 24, Oct 25	2
Intensive 3	NyShTsWnWz	Oct12	1
	NyTsWnWz	Nov 30, Dec 07	2
Total			104
2016	**Baseline**	**Period**	**# of sessions**
Intensive 2	TsWz	Jan 02 – Dec 31	88
	IsTsWz	Oct 08 – Dec 18	12
	IsWz	Oct 07 – Dec 27	15
Total			115

4.2 AOV

AOV was established in 2014 and started regular observations from 2015. Six AOV sessions were performed every year, and the Tsukuba Correlator took charge of the correlation of half of the sessions every year. Most of the data were transferred via the broadband network from not only Japan, but also China, Korea, Australia, and New Zealand, while the data of Syowa were only

Fig. 2 View of the backup system.

shipped to Japan. In addition, some stations sent data in real-time for ultra-rapid EOP estimation testing.

4.3 JADE and JAXA

JADE is a domestic geodetic VLBI series involving four GSI stations (Tsukuba, Ishioka, Aira, and Chichijima), three NICT stations (Kashima 34-m, Kashima 11-m, and Koganei 11-m), and one VERA station of the National Astronomical Observatory of Japan (NAOJ) located in Mizusawa. 18 JADE sessions were correlated in 2015. Because Aira and Chichijima were closed in 2015, JADE sessions were also finished at the end of 2015. The JAXA sessions are conducted separately from JADE, including JAXA stations, such as Usuda, in order to determine the global positions of the stations within ITRF. One JAXA session was processed in each year.

5 Outlook

We will continue to process the IVS Intensive sessions. For more stable operation, we will make further improvements to the *rapid_* programs and maintain the hardware and the network. We will also process the observed data of AOV sessions to play a major role in AOV as a correlator. Furthermore, we will try to process broadband observation data in order to explore the possibility of being a future VGOS correlator.

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2. Hobiger, T., et al.: Fully automated VLBI analysis with c5++ for ultra-rapid determination of UT1, *Earth Planets Space*, **62**, 933–937, 2010.

Washington Correlator

David M. Hall

Abstract This report summarizes the activities of the Washington Correlator for the years 2015 and 2016. The Washington Correlator provides up to 80 hours of attended processing per week plus up to 40 hours of unattended operation, primarily supporting Earth Orientation and astrometric observations.

1 General Information

The Washington Correlator (WACO) is located at and staffed by the U.S. Naval Observatory (USNO) in Washington, DC, USA. The correlator is sponsored and funded by the National Earth Orientation Service (NEOS), which is a joint effort of the USNO and NASA. Dedicated to processing geodetic and astrometric VLBI observations, the facility spent 100 percent of its time on these sessions. All of the weekly IVS-R4 sessions, all of the IVS-INT01 Intensives, and the APSG and CRF sessions were processed at WACO. The facility houses the WACO DiFX correlator.

2 Activities during the Past Two Years

- The Washington Correlator made the transition from the ageing Mark IV correlator to the new DiFX software correlator. Work to achieve the final configuration of the DiFX correlator, its associated servers, and its network is ongoing.
- The correlator staff continues the testing and repair of Mark 5 modules.
- Intensive observations from Kokee Park and Wettzell were routinely transferred via e-VLBI. 24-hour sessions from both Hobart antennas, Katherine, Yarragadee, Warkworth, Ny-Ålesund, Fortaleza, Yebes, Noto, HartRAO, Wettzell, Tsukuba, Aira, Kashima, Chichijima, and Sintotu were also transferred by high-speed networks.

U. S. Naval Observatory

Washington Correlator

IVS 2015+2016 Biennial Report

3 Staff

The Washington Correlator is under the management and scientific direction of the Earth Orientation Department of the U.S. Naval Observatory. Staffing problems have been persistent at WACO. In 2016, Daniel Veillette left the VLBI division for another position at USNO. Expedited efforts to hire a replacement and fill an additional position that had been approved led to two new astronomer positions in the VLBI division. In addition a contract for two FTE correlator scientists was executed bringing the senior scientific staff to four.

Table 1 Staff.

Staff	Duties
David Hall	Chief, VLBI Division
Phillip Haftings	Astronomer
Andrew Sargent	Astronomer
Bruce Thornton	Physical Science Technician
Roxanne Inniss	Media Librarian

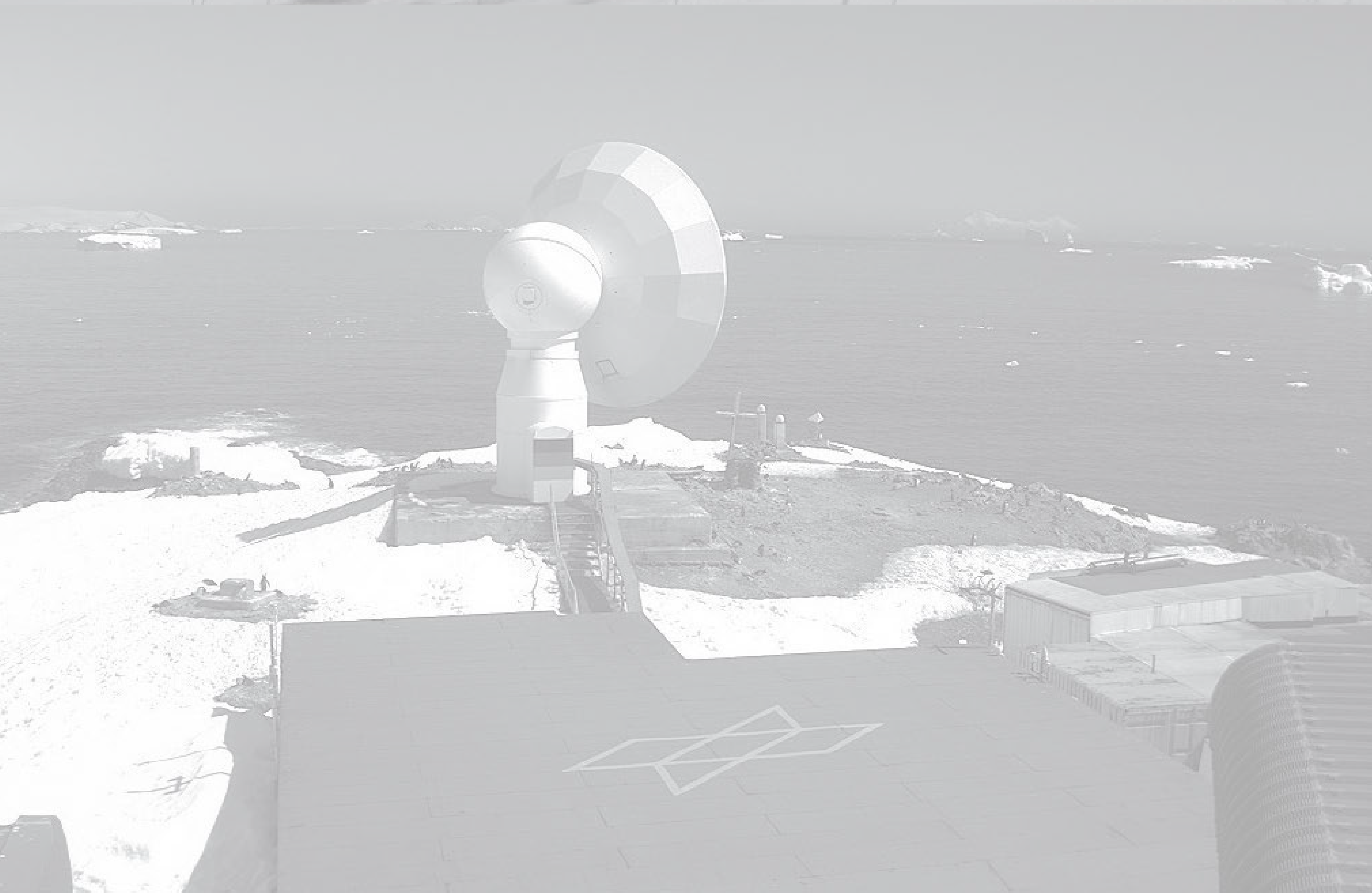
Table 2 Contractors.

Contractors	Company
John Spitzak	CPI
Matthew Hardin	USRA
Khalil Suliman	USRA

4 Future Plans

A hardware refresh is planned for the next fiscal year in addition to the expansion of file storage space. Upgrading the high-speed internet connection from 1 Gb/s to 10 Gb/s is also planned for the future.

Data Centers



BKG Data Center

Volkmar Thorandt, Reiner Wojdziak

Abstract This report summarizes the activities and background information of the IVS Data Center for the years 2015 and 2016. Included are information about functions, structure, technical equipment, and staff members of the BKG Data Center.

1 BKG Data Center Functions

The BKG (Federal Agency for Cartography and Geodesy) Data Center is one of the three IVS Primary Data Centers. It archives all VLBI-related data of IVS components and provides public access for the community. The BKG Data Center is connected to the OPAR and GSFC CDDIS Data Centers by mirroring the OPAR and the CDDIS file stocks several times per day. The sketch in Figure 1 shows the principle of mirroring.

IVS components can choose one of these Data Centers to put their data into the IVS archives by using its incoming area, which each Data Center has at its disposal. The BKG incoming area is protected, and users need to obtain a username and password to get access.

An incoming script watches the incoming area and checks the syntax of the files sent by IVS components. If it is okay, the script moves the files into the Data Center directories. Otherwise the files will be sent to a badfile area. Furthermore, the incoming script informs the responsible staff at the Data Center by sending e-mails about its activities. The incoming script is part of the technological unit which is responsible for managing the IVS and the Operational Data Center and for carrying out the first analysis steps in an automatic manner. All activities are monitored to guarantee data consistency and to control all analysis steps from data arrival to delivery of analysis products to IVS.

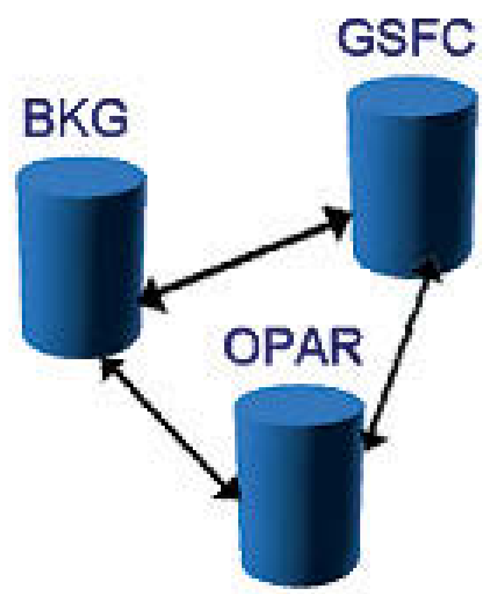


Fig. 1 Principle of mirroring.

Public access to the BKG Data Center is available through FTP and HTTP:

```
ftp://ivs.bkg.bund.de/pub/vlbi/

http://ivs.bkg.bund.de/vlbi/
```

BKG

BKG Data Center

IVS 2015+2016 Biennial Report

Structure of the BKG IVS Data Center:

```
vlbi/            : root directory
ivscontrol/      : controlfiles for the data center
ivsdata/         : VLBI observation files
ivsdocuments/    : IVS documents
ivsproducts/     : analysis products
    crf/         : celestial frames
    trf/         : terrestrial frames
    eops/        : earth orientation (24h sessions)
    eopi/        : earth orientation (Intensive sessions)
    daily_sinex/ : daily sinex files (24h sessions)
    int_sinex/   : daily sinex files (Intensive sessions)
    trop/        : troposphere
```

2 Technical Equipment

The BKG IVS Data Center is based on a DELL Server (SUSE Linux operating system), disk space of 500 GBytes (Raid system), and a backup system operated by an automatic tape library.

3 Staff Members

- Volkmar Thorandt (coordination, data analysis, data center, volkmar.thorandt@bkg.bund.de)
- Reiner Wojdziak (data center, Web design, reiner.wojdziak@bkg.bund.de)
- Dieter Ullrich (data analysis, data center, dieter.ullrich@bkg.bund.de)
- Gerald Engelhardt (data analysis, gerald.engelhardt@ bkg.bund.de)

CDDIS Data Center Summary for the IVS 2015–2016 Biennial Report

Carey Noll

Abstract This report summarizes activities during the years 2015 through 2016 and the future plans of the Crustal Dynamics Data Information System (CDDIS) with respect to the International VLBI Service for Geodesy and Astrometry (IVS). Included in this report are background information about the CDDIS, the computer architecture, archive contents, and future plans for the CDDIS within the IVS.

1 General Information

The Crustal Dynamics Data Information System (CDDIS) has supported the archiving and distribution of Very Long Baseline Interferometry (VLBI) data since its inception in 1982. The CDDIS is a central facility that provides users access to data and derived products to facilitate scientific investigation. The CDDIS archive of GNSS (e.g., GPS, GLONASS), laser ranging, VLBI, and DORIS data is stored online for remote access. Information about the system is available via the Web at the URL https://cddis.nasa.gov. In addition to the IVS, the CDDIS actively supports other IAG services including the International GNSS Service (IGS), the International Laser Ranging Service (ILRS), and the International DORIS Service (IDS), as well as the International Earth Rotation and Reference Systems Service (IERS) and the IAG's observing system, the Global Geodetic Observing System (GGOS). The current and future plans for the system's support of the IVS are discussed below.

NASA Goddard Space Flight Center

CDDIS Data Center

IVS 2015+2016 Biennial Report

2 System Description

The CDDIS archive of VLBI data and products is accessible to the public through anonymous ftp (ftp://cddis.nasa.gov) and the Web (https://cddis.nasa.gov/archive).

2.1 Computer Architecture

The CDDIS is operational on a dedicated server, cddis.nasa.gov. The CDDIS is located at NASA GSFC and is accessible to users 24 hours per day, seven days per week. As of the end of 2016, over 260 Gbytes are devoted to VLBI activities.

In 2015, the CDDIS procured a new system for operational support. Transition to the new CDDIS computer hardware was completed in late November 2016. This new system configuration now provides a more reliable/redundant environment (e.g., power, HVAC, 24-hour on-site emergency personnel) and network connectivity for CDDIS; a disaster recovery system is installed in a different location on the GSFC campus. The new system location addresses a long-time concern for the CDDIS, namely, the lack of consistent and redundant power and cooling in its existing computer facility. Multiple redundant 40G network switches are utilized to take full advantage of a high-performance network infrastructure by utilizing fully redundant network paths for all outgoing and incoming streams along with dedicated 10G network connections between its primary operations and its backup operations. The CDDIS transitioned the majority of its operation services to virtual machine (VM) technology for both multiple instance services in a load balancing configuration which allows additional instances to be increased or decreased due to demand and allows maintenance (e.g., patching, upgrades) to proceed without interruption to the user or any downtime. CDDIS now utilizes a unified storage system (100 Tbytes in size) to easily accommodate future growth of the archive and facilitate near real-time replication between its production and disaster recovery sites. A schematic diagram of the new CDDIS architecture is shown in Figure 1.

CDDIS has put into operation a complete rewrite of its file ingest processing software in 2016. This rewrite incorporated numerous disparate programs developed over the years into a single, easily maintained software base which incorporates all the CDDIS requirements for data ingest while also allowing additional flexibility in meeting future metadata requirements. The software was initially modified for incoming GNSS files but will be extended to all incoming files, including DORIS data and products, in the near future.

2.2 File Submissions

One requirement of the new CDDIS computer system involved a change to the file upload process. In the old system, CDDIS used ftp for delivery of data for the archive from both data centers and analysis centers. While this has worked well over the years, transition to the new system provided an opportunity to update this method to a Web-based approach that can utilize a different user sign-on/authentication infrastructure. CDDIS developed a Web-based application that allows users to use existing scripts without significant modification but also tie authentication into the NASA system. Staff worked with the groups who submit VLBI data and IVS products to CDDIS to transition their procedures to the new file upload system.

3 Archive Content

The CDDIS has supported GSFC VLBI and IVS archiving requirements since 1979 and 1999, respectively.

The IVS Data Center content and structure is shown in Table 1 (a figure illustrating the flow of information, data, and products between the various IVS components was presented in the CDDIS submission to the IVS 2000 Annual Report). As described above, the CDDIS has established a file upload system for providing IVS data, product, and information files to the archive. Using specified filenames, Operation and Analysis Centers upload files to this system. Automated archiving routines, developed by GSFC VLBI staff, peruse the directories and move any new data to the appropriate public disk area. These routines migrate the data based on the filename to the appropriate directory as described in Table 1. Index files in the main sub-directories under ftp://cddis.nasa.gov/vlbi are updated to reflect data archived in the filesystem. Furthermore, mirroring software was installed on the CDDIS host computer, as well as all other primary IVS Data Centers, to facilitate equalization of data and product holdings among these Data Centers. At this time, mirroring is performed between the IVS Data Centers located at the CDDIS, the Bundesamt für Kartographie und Geodäsie in Leipzig, and the Observatoire de Paris.

The public file system in Table 1 on the CDDIS computer, accessible via anonymous ftp, consists of a data area, which includes auxiliary files (e.g., experiment schedule information, session logs) and VLBI data (in both database and NGS card image formats). A products disk area was also established to house analysis products from the individual IVS Analysis Centers as well as the official combined IVS products. A documents disk area contains format, software, and other descriptive files.

4 Data Access

During 2015–2016, over 2,700 distinct hosts accessed the CDDIS on a yearly basis to retrieve VLBI related files. These users, which include other IVS Data Centers, downloaded over 1.8 Tbytes (2.1 M files) of data and products from the CDDIS VLBI archive in 2016.

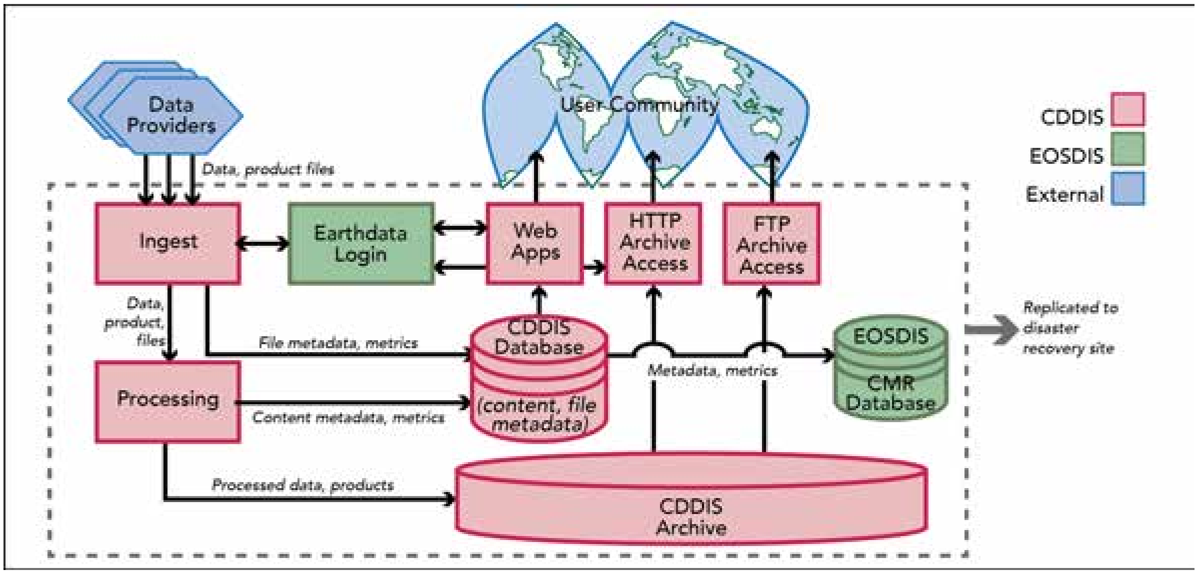


Fig. 1 System architecture overview diagram for the new CDDIS facility installation within the EOSDIS infrastructure.

Table 1 IVS data and product directory structure.

Directory	Description
Data Directories	
vlbi/ivsdata/db/*yyyy*	VLBI database files for year *yyyy*
vlbi/ivsdata/ngs/*yyyy*	VLBI data files in NGS card image format for year *yyyy*
vlbi/ivsdata/aux/*yyyy*/*ssssss*	Auxiliary files for year *yyyy* and session *ssssss*; these files include: log files, wx files, cable files, schedule files, correlator notes
Product Directories	
vlbi/ivsproducts/crf	CRF solutions
vlbi/ivsproducts/eopi	EOP-I solutions
vlbi/ivsproducts/eops	EOP-S solutions
vlbi/ivsproducts/daily_sinex	Daily SINEX solutions
vlbi/ivsproducts/int_sinex	Intensive SINEX solutions
vlbi/ivsproducts/trf	TRF solutions
vlbi/ivsproducts/trop	Troposphere solutions
Project Directories	
vlbi/ITRF2013	IVS contributions to the ITRF 2013 efforts
vlbi/ITRF2014	IVS contributions to the ITRF 2014 solution
vlbi/ivs-pilotbl	IVS Analysis Center pilot project (baseline)
Other Directories	
vlbi/ivscontrol	IVS control files (master schedule, etc.)
vlbi/ivsdocuments	IVS document files (solution descriptions, etc.)
vlbi/raw	Raw VLBI data
vlbi/dserver	dserver software and incoming files

5 Future Plans

The CDDIS staff will continue to work closely with the IVS Coordinating Center staff to ensure that our system is an active and successful participant in the IVS archiving effort. CDDIS staff will further work with the IVS CC to integrate VLBI data and product files into the updated operations software recently installed on the new CDDIS system.

The CDDIS has established Digital Object Identifiers (DOIs) for several of its GNSS data sets; website "landing" pages have been established for these published DOIs. DOIs for additional items, including VLBI data and products, are under development and review prior to registering and implementation.

Italy INAF Data Center Report

Monia Negusini, Pierguido Sarti

Abstract This report summarizes the activities of the Italian INAF VLBI Data Center. Our Data Center is located in Bologna, Italy and belongs to the Institute of Radioastronomy, which is part of the National Institute of Astrophysics.

1 Introduction

The main analysis activity and storage is concentrated in Bologna, where we store and analyze single databases, using CALC/SOLVE. The νSolve software has been installed but not routinely used yet.

The IRA started to store geodetic VLBI databases in 1989; at the very beginning the databases archived in Bologna mostly contained data including European antennas from 1987 onward. In particular, most of the databases available here had VLBI data with at least three European stations. Additionally, we stored all the databases with the Ny-Ålesund antenna observations. In 2002, we decided to store the complete set of databases available on the IVS Data Centers, although we limited the time span to the observations performed from 1999 onwards. All the databases were processed and saved with the best selection of parameters for the final arc solutions. In order to perform global solutions, we have computed and stored the superfiles for all the databases. In some cases we have introduced GPS-derived wet delays into the European databases (1998 and 1999 EUROPE sessions, for the time being), as if they were produced by a WVR. These databases are available and stored with a different code from the original databases. In order to produce these databases, we have modified DBCAL, and this new version is available to external users.

Moreover, few Italian VLBI (VITA) experiments have been performed in the last years and the relevant databases are available.

Istituto di Radioastronomia INAF, Bologna

2 Computer Availability and Routing Access

To date, the main computer is a Linux workstation, on which the latest release of the Mark 5 Calc/Solve is installed and to which all VLBI data analysis was migrated. The Internet address of this computer is geovlbi.ira.inaf.it. Since 2016, a new server with a storage capacity of 11 TB has been available, and therefore all experiments performed in the previous years were downloaded and archived, thus completing the catalog. The older experiments will be analyzed in order to perform global long-term analysis. At present, the databases are stored in the following directories:

1 = /iranet/geo/dbase1
2 = /iranet/geo/dbase2
3 = /iranet/geo/dbase
4 = /iranet/geo/dbase3
5 = /iranet/geo/dbase4

The superfiles are stored in: /iranet/geo/super1. The list of superfiles is stored in the file /iranet/geo/solve/mk5/save_files/SUPCAT. The username for accessing the databases is geo. The password may be requested by sending an e-mail to negusini@ira.inaf.it.

NICT Data Center Biennial Report for 2015–2016

Mamoru Sekido

Abstract The Data Center at the National Institute of Information and Communications Technology (NICT) archives and releases the databases and analysis results processed at NICT. Regular VLBI sessions of the Key Stone Project VLBI Network were the primary objective of the Data Center. These regular sessions continued until the end of November 2001. In addition to the Key Stone Project VLBI sessions, NICT has been conducting geodetic VLBI sessions for various purposes, and these data are also archived and released by the Data Center.

1 General Information

The IVS Data Center at National Institute of Information and Communications Technology (NICT) archives and releases the databases and analysis results processed at NICT. Major parts of the data are from the Key Stone Project (KSP) VLBI sessions [1], but other regional and international VLBI sessions conducted by NICT are also archived and released. Since routine observations of the KSP network terminated at the end of November 2001, there have been no additional data from the KSP regular sessions since 2002.

The analysis results in SINEX (Solution INdependent EXchange) format, as well as in other formats, are available on the WWW server. Database files of non-KSP sessions, i.e., other domestic and international geodetic VLBI sessions, are also available on the WWW server. Table 1 lists the WWW server locations maintained by the NICT Data Center.

National Institute of Information and Communications Technology (NICT)

NICT Data Center

IVS 2015+2016 Biennial Report

2 Activities during the Past Two Years

2.1 KSP VLBI Sessions

The KSP sessions had been performed with four VLBI Stations at Kashima, Koganei, Miura, and Tateyama on a daily or bi-daily basis until May 1999. The high-speed ATM (Asynchronous Transfer Mode) network line to the Miura station became unavailable in May 1999, and real-time VLBI observations with the Miura station became impossible. Thereafter, the real-time VLBI sessions were performed with the three other stations. Once every six days (every third session), the observed data was recorded to the K4 data recorders at the three stations, and the Miura station participated in the sessions with the tape-based VLBI technique. In this case, the observed data at the three stations other than the Miura station were processed in real-time, and the analysis results were released promptly after the observations were completed. A day later, the observed tapes were transported from the Kashima, Miura, and Tateyama stations to the Koganei station for tape-based correlation processing with all six baselines. After the tape-based correlation processing was completed, the data set produced with the real-time VLBI data processing was replaced by the new data set.

In July 2000, unusual site motion of the Tateyama station was detected from the KSP VLBI data series, and the frequency of the sessions was increased from once every two days to daily on July 22. The daily sessions were continued until November 11, 2000, and the

Table 1 URLs of the WWW server systems. The last two URLs have slightly changed.

Service	URL
KSP WWW pages	`http://ksp.nict.go.jp/`
IVS WWW mirror pages	`http://ivs.nict.go.jp/mirror/`
Database files	`http://www2.nict.go.jp/sts/stmg/www3/database/`
e-VLBI UT1 Exp.	`http://www2.nict.go.jp/sts/stmg/research/e-VLBI/UT1/`

site motions of the Tateyama and Miura stations were monitored in detail. During the period, it was found that Tateyama station moved about 5 cm to the northeast direction. The Miura station also moved about 3 cm to the north. The unusual site motions of these two stations gradually settled, and the current site velocities seem to be almost the same as those before June 2000. According to investigation of the time series of the site positions, the unusual site motion started sometime between the end of June 2000 and the beginning of July 2000. At the same time, volcanic and seismic activities near the Miyakejima and Kozushima Islands began. These activities have been finally found to be the cause of the regional crustal deformation in the area.

2.2 UT1 e-VLBI Sessions

In the period from 2007 to 2008, experimental e-VLBI sessions for rapid UT1 determination were conducted in collaboration with NICT, GSI, the Onsala Space Observatory, and the Metsähovi VLBI station. Observed VLBI data were transferred to Kashima (NICT) or Tsukuba (GSI) via a high-speed Internet network, and then succeeding correlation and bandwidth synthesis processes were applied in a pipeline scheme to make quick estimation of UT1-UTC. The VLBI data from these experiments are saved in Mark III database format and are available from this Data Center.

3 Current Status

The VLBI project of our group is currently focused on development of a broadband system and its application to frequency transfer. Two sets of small diameter VLBI stations are placed at NICT Headquarters in Tokyo and at the National Metrology Institute of Japan in Tsukuba city. The Kashima 34-m VLBI station has been upgraded to enable broadband observing. In addition to these three stations, the Ishioka 13-m VGOS station (GSI) has been used for domestic broadband R&D experiments [2]. These data are also saved in Mark III databases and analyzed by the CALC/SOLVE system. These data will be placed in the NICT Data Center in the near future.

References

1. Special issue for the Key Stone Project, J. Commun. Res. Lab., Vol. 46, No. 1, March 1999.

2. Mamoru Sekido, "NICT VLBI Analysis Center Report for 2015–2016", International VLBI Service for Geodesy and Astrometry 2015+2016 Biennial Report, edited by K. D. Baver, D. Behrend, and K. L. Armstrong, this volume.

Paris Observatory (OPAR) Data Center

Christophe Barache, Teddy Carlucci, Sébastien Lambert

Abstract This report summarizes the OPAR Data Center activities in 2015–2016. Included is information about functions, architecture, status, future plans, and staff members of OPAR Data Center.

1 General Information

The Paris Observatory (OPAR) has provided a Data Center for the International VLBI Service for Geodesy and Astrometry (IVS) since 1999. The OPAR as well as CDDIS and BKG is one of the three IVS Primary Data Centers. Their activities are done in close collaboration for collecting files (data and analysis files), and making them available to the community as soon as they are submitted. The three primary Data Centers have a common protocol and each of them:

- has the same directory structure (with the same control file),
- has the same script,
- is able to receive all IVS files (auxilliary, database, products, documents),
- mirrors the other ones every three hours,
- gives free FTP access to the files.

This protocol gives the IVS community a transparent access to a Data Center through the same directory, and a permanent access to files in case of a Data Center breakdown.

SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, LNE, 61 av de l'Observatoire, 75014 Paris, France

Paris Observatory (OPAR) Data Center

IVS 2015+2016 Biennial Report

To be able to submit a file to a Data Center, Operational and Analysis Centers have to be registered by the IVS Coordinating Center. The file names have to conform to the name conventions. A script checks the file and puts it in the right directory. The script undergoes permanent improvement and takes into account the IVS components' requests.

2 Current Status

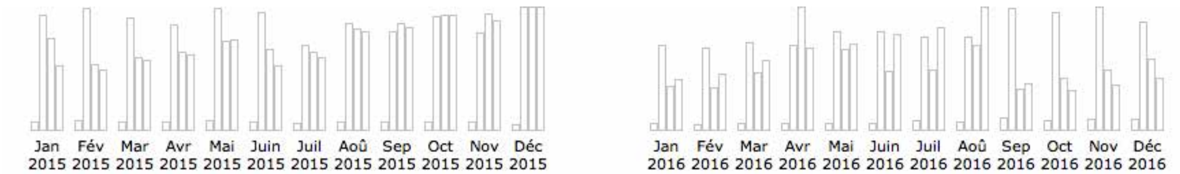
The OPAR Data Center is currently operated on a PC Server (PowerEdge 2800 - Xeron 3.0 GHz) located at Paris Observatory, and running the Fedora Linux operating system. To make all IVS products available online, the disk storage capacity was significantly increased and the server is equipped now with RAID 3 TB disk extensible up to 4.7 TB. The OPAR server is accessible 24 hours per day, seven days per week through Internet connection with 2 Mbit/s rate. Users can get the IVS products by using the FTP protocol. Access to this server is free for users.

FTP access:

ivsopar.obspm.fr
username : anonymous
password : your e-mail
cd vlbi (IVS directory)

3 Staff Members

Christophe Barache is in charge of the maintenance of the Data Center. For hardware issues, he is helped by Teddy Carlucci, who is one of the IT managers of



Mois	Visiteurs différents	Visites	Hits	Bande passante
Jan 2015	103	1283	215250	210.79 Go
Fév 2015	108	1359	153406	197.88 Go
Mar 2015	95	1250	169393	231.98 Go
Avr 2015	95	1177	182562	248.35 Go
Mai 2015	107	1358	207511	296.50 Go
Juin 2015	104	1311	188203	211.14 Go
Juil 2015	89	945	181742	237.60 Go
Aoû 2015	96	1188	235556	325.58 Go
Sep 2015	92	1101	248253	337.26 Go
Oct 2015	105	1264	269694	375.61 Go
Nov 2015	105	1079	273142	359.48 Go
Déc 2015	75	1360	286171	401.88 Go
Total	1174	14675	2610883	3434.04 Go

Mois	Visiteurs différents	Visites	Hits	Bande passante
Jan 2016	99	1219	160626	177.11 Go
Fév 2016	93	1188	155359	196.05 Go
Mar 2016	100	1258	208821	240.70 Go
Avr 2016	100	1235	445988	285.32 Go
Mai 2016	115	1420	295614	297.31 Go
Juin 2016	115	1427	214409	332.15 Go
Juil 2016	147	1336	218937	355.14 Go
Aoû 2016	137	1346	312163	422.34 Go
Sep 2016	195	1749	151625	163.87 Go
Oct 2016	152	1703	192788	138.47 Go
Nov 2016	170	1767	218350	158.08 Go
Déc 2016	171	1560	260044	179.19 Go
Total	1594	17208	2834724	2945.74 Go

Fig. 1 OPAR Data Center access statistics for (left) 2015 and (right) 2016.

the SYRTE department. Sébastien Lambert is in charge of the IVS activities at the SYRTE department including also the scientific management of the IVS Analysis Center.

To request more information about the OPAR Data Center please contact ivs.opa@obspm.fr

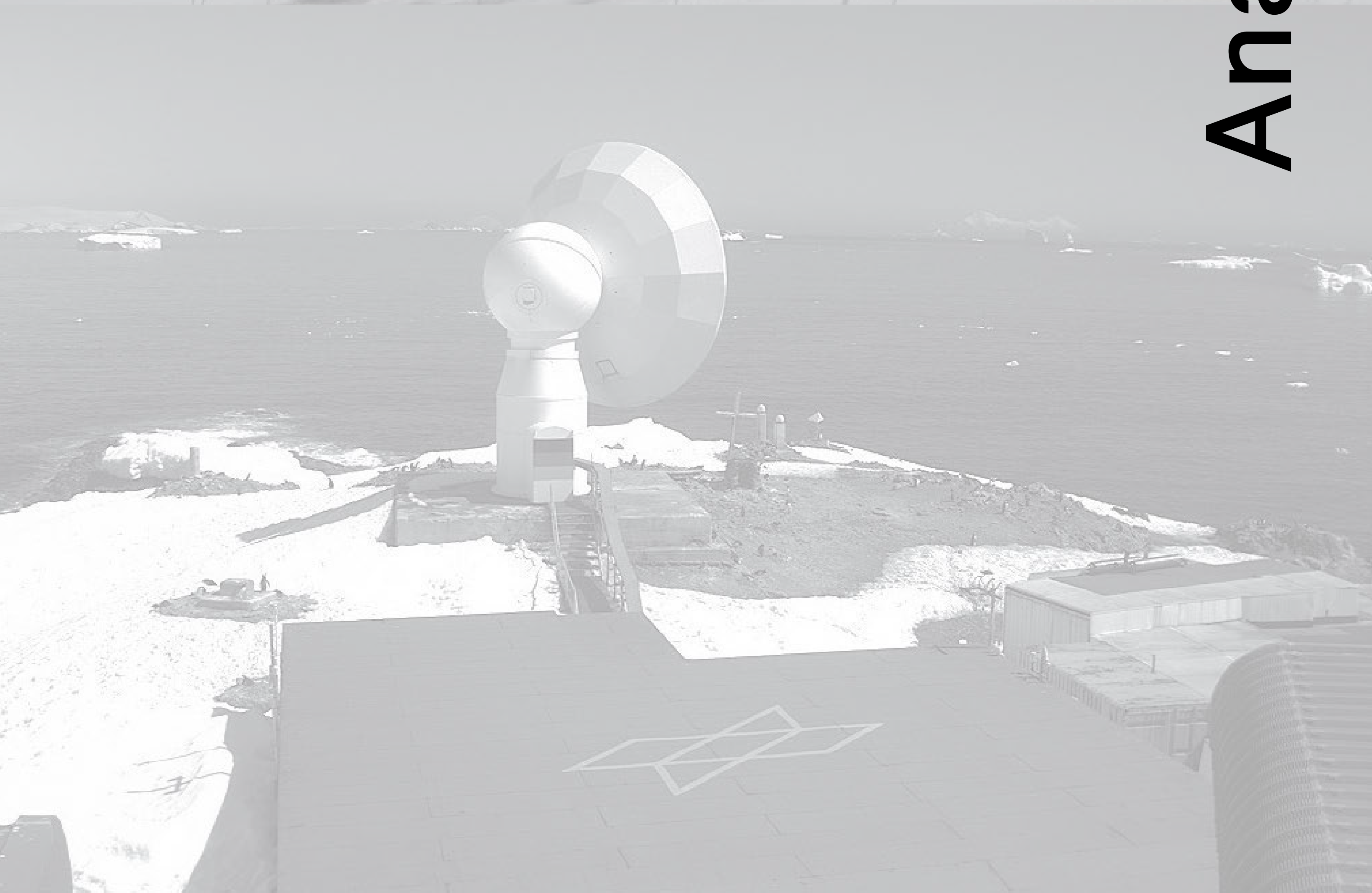
4 Activities during the Past Years

The FTP access statistics for the last two years are shown in Figure 1.

5 Future Plans

The OPAR Data Center will be installed on a new server in March 2017 running Linux Debian 8.6.

Analysis Centers



Analysis Center of Saint Petersburg University

Dmitriy Trofimov, Veniamin Vityazev

Abstract This report briefly summarizes the activities of the Analysis Center of Saint Petersburg University during 2015 and 2016. The current status as well as our future plans are described.

1 General Information

The Analysis Center of Saint Petersburg University (SPU AC) was established at the Sobolev Astronomical Institute of the SPb University in 1998. The main activity of the SPU AC for the International VLBI Service before 2007 consisted of routine processing of 24-hour and one-hour observational sessions for obtaining Earth Orientation Parameters (EOP) and rapid UT1-UTC values, respectively. In 2008, we began submitting the results of 24-hour session processing.

2 Component Description

Currently, we support two series of Earth Orientation Parameters: spu00004.eops and spu2015a.eops.

All parameters were adjusted using the Kalman filter technique. For all stations (except the reference station), the wet delay, clock offsets, clock rates, and troposphere gradients were estimated. Troposphere wet delay and clock offsets were modeled as a stochastic process such as a random walk. The clock rates and the troposphere gradients were considered to be the constant parameters.

Sobolev Astronomical Institute of Saint Petersburg University

AI SPbU Analysis Center

IVS 2015+2016 Biennial Report

The main details of the solutions of the EOP time series spu00004.eops and spu2015a.eops are summarized below:

- data span: 1989.01–2016.12
- CRF: fixed to ICRF-Ext.2
- TRF: VTRF2005 was used as an a priori TRF
- estimated parameters:

  1. EOP: x,y, UT1–UTC, dψ,dε;
  2. Troposphere: troposphere gradients were estimated as constant parameters, and wet troposphere delays were modeled as a random walk process;
  3. Station clocks were treated as follows: offset as a random walk process, rate as a constant.

- nutation model: IAU 1980 (spu00004.eops), IAU 2000 (spu2015a.eops)
- mapping function: VMF1
- technique: Kalman filter
- software: OCCAM v.6_2

3 Staff

The assistant professor of Saint Petersburg University, Dmitriy Trofimov, was in charge of the routine processing of the VLBI observations. General coordination and support for the activities of the SPU AC at the Astronomical Institute were performed by Professor Veniamin Vityazev.

4 Current Status and Activities

In 2015–2016, the routine estimation of the five Earth Orientation Parameters was performed. The OCCAM software package (version 6_2) was used for current processing of VLBI data [1]. The time series is named spu00004.eops. It includes data obtained by the IRIS-A, NEOS-A, R1, R4, RDV, and R&D observing programs, and it covers 28 years of observations (from January 2, 1989 until the end of 2016). The total number of VLBI sessions processed at the SPU AC is about 2,230, of which about 160 sessions were processed in 2015–2016.

A new Earth Orientation Parameters series was begun in 2015 and was named spu2015a.eops. The total number of points is about 2,220; in 2015–2016 about 160 points were added.

Our experience and the equipment of the Analysis Center was used for giving lectures and practical work on the basics of radio interferometry to university students. We use our original manual on the training in modern astrometry and, in particular, VLBI [2].

5 Future Plans

In 2017, we are going to continue our regular processing of the VLBI sessions as well as giving lectures and practical training for students in a special course on radio astrometry. This course is a part of the systematic curriculum of astronomical education at SPb University.

Acknowledgements

In 2015 and 2016 the work of the SPU AC was performed within the project "Determination of the Earth Orientation Parameters required for launching missiles to asteroids" (SPU grant 6.37.343.2015).

References

1. O. Titov, V. Tesmer, J. Boehm. OCCAM v. 6. 0 Software for VLBI Data Analysis, In International VLBI Service for Geodesy and Astrometry 2004 General Meeting Proceedings, N. R. Vandenberg and K. D. Baver (eds.), NASA/CP-2004-212255, pp. 267–271, 2004.
2. V. Vityazev, I. Guseva, V. Kiyaev, M. Mishchenko, O. Titov, A. Tsvetkov. Celestial and Terrestrial Coordinates (In Russian), Manual on Astrometry, p. 301, SPb University, 2011.

Geoscience Australia Analysis Center 2015-2016 Biennial Report

Oleg Titov

Abstract This report gives an overview of the activities of the Geoscience Australia IVS Analysis Center during 2015-2016.

1 General Information

The Geoscience Australia (GA) IVS Analysis Center is located in Canberra within the Geodesy Section, Geodesy and Seismic Monitoring Group, Community Safety and Earth Monitoring Division (CSEMD).

2 Activities during the Past Years

Several celestial reference frame (CRF) solutions have been prepared using the OCCAM 6.3 software. The latest solution (ICRF3 prototype) was released in September 2016. VLBI data from 4,725 daily sessions observed from December 1983 to June 2016 have been used to compute several global solutions with different sets of reference radio sources. This includes 7,690,017 observational delays from 3,966 radio sources having three or more observations.

Station coordinates were also estimated using No-Net-Rotation (NNR) and No-Net-Translation (NNT) constraints. The long-term time series of the station coordinates have been used to estimate the corresponding velocities for each station. The tectonic motion for the Gilcreek VLBI site after the Denali earthquake was modeled using an exponential function typical of post-seismic deformation.

The adjustment was made by least-squares collocation, which considers the clock offsets, wet troposphere delays, and tropospheric gradients as stochastic parameters with *a priori* covariance functions. The gradient covariance functions were estimated from GPS hourly values.

In 2015-2016, all three new AuScope 12-meter radio telescopes were actively working in different IVS geodetic and astrometric programs. Another radio telescope, Hobart26, operated by the University of Tasmania (UTAS), participated in the geodetic VLBI programs occasionally. The AuScope network runs some special sessions in addition to the routine activities of the regular IVS programs. In particular, three sessions were organized in 2014-2016 (19 Oct 2014, 9 Jan 2015, and 8 Oct 2016) to observe reference radio sources near the Sun. Data from the first two sessions were successfully correlated and reduced, and the third session is in progress.

Acknowledgements

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Geoscience Australia

GA Analysis Center

IVS 2015+2016 Biennial Report

Report for 2015–2016 from the Bordeaux IVS Analysis Center

Patrick Charlot, Antoine Bellanger, Romuald Bouffet, Géraldine Bourda, Arnaud Collioud, Alain Baudry

Abstract This report summarizes the activities of the Bordeaux IVS Analysis Center in 2015 and 2016. The work in that period was focused primarily on (i) the regular analysis of the IVS-R1 and IVS-R4 sessions with the GINS software package; (ii) the systematic VLBI imaging of the RDV sessions and calculation of the corresponding source structure index and compactness values, and (iii) the involvement in the IAU Working Group on the next ICRF (International Celestial Reference Frame) realization. The latter is concerned with the assessment of source quality and the identification of transfer sources for the alignment between the ICRF and the future Gaia optical frame. Since summer 2015, a member of the Bordeaux group also has chaired the Working Group. Apart from these activities, the year 2016 was also marked by the move from the historical site of the *Observatoire de Bordeaux* to new premises on the campus of the University of Bordeaux.

1 General Information

The *Laboratoire d'Astrophysique de Bordeaux (LAB)* is a research center which is funded by the University of Bordeaux and the *Centre National de la Recherche Scientifique (CNRS)*. It is part of a bigger institute, the *Observatoire Aquitain des Sciences de l'Univers (OASU)*, formerly Bordeaux Observatory. The OASU has a wider scope, covering environmental sciences besides historic activities in astronomy and astrophysics. A specific role of the observatory is to provide support for acquiring, analyzing, and archiving observations of various types in these fields, including participation in national and international services, such as the IVS.

Laboratoire d'Astrophysique de Bordeaux

Bordeaux Analysis Center

IVS 2015+2016 Biennial Report

Fig. 1 The new OASU building that has hosted the LAB and the Bordeaux IVS Analysis Center on the Campus of the University of Bordeaux in Pessac since June 2016.

A major event happened in the spring of 2016 with the relocation of the 130-year old observatory from its historical site in Floirac [1] to its new premises $\sim$ 15 km away on the campus of the University of Bordeaux in Pessac, where a dedicated building was constructed for the OASU (Figure 1). The new premises offer individual offices, purpose-built laboratories (electronics, mechanics, etc.), and modern conference rooms (ready for videoconferencing). The new address is the following:

Laboratoire d'Astrophysique de Bordeaux
Observatoire Aquitain des Sciences de l'Univers
Université de Bordeaux - Bât. B18N
Allée Geoffroy Saint Hilaire, CS 50023
33615 Pessac Cedex, France

VLBI activities within the LAB are primarily developed within the M2A team (*Métrologie de l'espace, Astrodynamique, Astrophysique*). The contribution of the group to IVS has been mostly concerned with the maintenance, extension, and improvement of the International Celestial Reference Frame (ICRF). This includes regular imaging of the ICRF sources and evaluation of their astrometric suitability, as well as developing specific VLBI observing programs for enhancing the celestial frame. In addition, the group is in charge of the VLBI component of the GINS software package, a multi-technique software developed by the CNES (*Centre National d'Etudes Spatiales*) which has the ability to process data from most space geodetic techniques, including GNSS, VLBI, DORIS, SLR, LLR, satellite altimetry, and other space missions [2].

2 Description of Analysis Center

The Bordeaux IVS group routinely analyzes the IVS-R1 and IVS-R4 sessions with the GINS software package. From these sessions, weekly solutions estimating EOPs with six-hour resolution are produced. Until 2015, the primary objective of such analyses was the integration of the corresponding VLBI data into multi-technique solutions combining VLBI and other space geodetic data (SLR, GPS, and DORIS) at the observation level through a collaborative effort within the French *Groupe de Recherches de Géodésie Spatiale (GRGS)*, as noted in previous reports. With the termination of this activity, the focus is now placed upon developing an operational VLBI analysis with the goal of contributing to the rapid IVS primary EOP combination.

The group is also focused on imaging the ICRF sources on a regular basis by systematic analysis of the data from the RDV sessions, which are conducted six times a year. This analysis is carried out with the AIPS and DIFMAP software packages. The aim of such regular imaging is to characterize the astrometric suitability of the sources based on the so-called "structure index" and to compare source structural evolution and positional instabilities. Such studies are essential for identifying sources of high astrometric quality, which is required, e.g. for the construction of ICRF3 or for selecting proper sources for aligning the Gaia frame.

3 Scientific Staff

During 2015 and 2016, six individuals contributed to one or more of our IVS analysis and research activities. A description of what each person worked on, along with the time spent on it, is given below. It is to be noted that Romuald Bouffet defended his Ph. D. thesis on 16 June 2015 [3]. He then left the field and now works for industry. Apart from this change, there were no other changes in the IVS staff over the period.

- Patrick Charlot (30%): researcher with overall responsibility for Analysis Center work and data processing. His interests include the ICRF densification, extension, and link to the Gaia frame, studies of radio source structure effects in astrometric VLBI data, and astrophysical interpretation. He has also been Chair of the IAU Working Group on the next ICRF realization since August 2015.
- Antoine Bellanger (100%): engineer with a background in statistics and computer science. He is tasked to process VLBI data with GINS and to develop procedures and analysis tools to automate such processing with prospects of implementing an operational VLBI analysis in the future.
- Romuald Bouffet (30%, until June 2015): Ph. D. student from the University of Bordeaux whose thesis was focused on the study of the relationship between radio source structure and position instabilities. His work was largely based on astrometric data and VLBI images derived from IVS sessions.
- Géraldine Bourda (50%): astronomer in charge of developing the VLBI part of GINS and responsible for the analysis results derived from GINS. She also leads a VLBI observational program for linking the ICRF and the future Gaia optical frame.
- Arnaud Collioud (90%): engineer with a background in astronomy and interferometry. His tasks are to image the sources in the RDV sessions using AIPS and DIFMAP, to develop the Bordeaux VLBI Image Database and *IVS Live* tool, and to conduct simulations for the next generation VLBI system.
- Alain Baudry (10%): radioastronomy expert with specific interest in radio source imaging and astrometric VLBI. He is a Professor Emeritus and is working part time as a co-investigator for developing upgrades of the ALMA mm/submm array.

4 Current Status

As noted above, one of our goals for the future is to implement an operational analysis of the IVS-R1 and IVS-R4 sessions for EOP determination using the GINS software package. To reach this goal, a prerequisite is to assess the quality of the results derived with GINS and to validate these against similar determinations obtained with other VLBI software packages, because GINS, in its VLBI capability, is not used by any other groups. To this aim, we joined the VLBI Analysis Software Comparison Campaign initiated by Chalmers University of Technology in the fall of 2015, the results of which were presented at the IVS 2016 General Meeting [4]. The comparison, however, turned out to be not fully conclusive for GINS. We were not sure that the total delay model, which was compared, was exactly identical in all of its components that were implemented in other VLBI software packages. A second stage, which compares the individual components of the delay model separately, is thus to be carried out.

Another major part of our activity consists of systematic imaging of the sources observed during the RDV sessions. During 2015 and 2016, eight such sessions were processed (from RDV96 to RDV110), resulting in 1,303 VLBI images at either X- or S-band for 415 different sources. The imaging work load has been shared with USNO since 2007 (starting with RDV61); the USNO group processes the odd-numbered RDV sessions while the Bordeaux group processes the even-numbered ones. The VLBI images are used in a second stage to derive structure correction maps and visibility maps along with values for structure indices and source compactness in order to assess astrometric source quality (see [5, 6] for a definition of these quantities). All such information is made available through the Bordeaux VLBI Image Database (BVID)[1]. At present, the BVID comprises a total of 5,179 VLBI images for 1,273 different sources (with links to an additional 6,775 VLBI images from the Radio Reference Frame Image Database of USNO), along with 11,744 structure correction maps and as many visibility maps.

Preparatory work for the realization of ICRF3 is an additional activity that gained increasing importance over the past two years. Two members of the group (Géraldine Bourda and Patrick Charlot) are members of the IAU Working Group on the next ICRF realization and as such contribute to the effort towards ICRF3. Their contribution has to do with (i) the assessment of astrometric source quality, a primary criterion to select ICRF3 defining sources, and (ii) the identification of proper transfer sources for the alignment of the future Gaia frame. Additionally, Patrick Charlot took over as Chair of the Working Group for the term 2015–2018, following appointment at the last IAU General Assembly in August 2015. In all, four face-to-face meetings of the Working Group were organized in 2015–2016 (Ponta Delgada, Azores, 21 May 2015; Honolulu, Hawaii, 6 August 2015; Ekudeni, South Africa, 16 March 2016, and Haystack, USA, 17-18 October 2016) along with three teleconferences in 2016, all of which were attended by at least one member from Bordeaux. Patrick Charlot also gave invited presentations about the progress on ICRF3 at the IVS 2016 General Meeting (Ekudeni, 13-17 March 2016), at a French workshop about fundamental physics and reference systems (Paris, 2-3 June 2016), and at the 13th EVN Symposium (St. Petersburg, Russia, 20-23 September 2016). The coming 1.5 years promise to be exciting, with ICRF3 to be completed by early 2018, for an adoption during the next IAU General Assembly in August 2018.

[1] The Bordeaux VLBI Image Database may be accessed at http://astrophy.u-bordeaux.fr/BVID.

5 Dissemination and Outreach

The *IVS Live* Web site[2], a specific tool developed by the Bordeaux group, provides "Live" information about ongoing IVS sessions, including VLBI images of the observed sources [7]. The Web site is updated automatically based on the IVS Master Schedule. At the end of 2016, 7,617 IVS sessions were available, featuring 2,118 sources, with 74 stations involved. Tracing the connections indicates that there were 1,331 visits (from 61 countries) in 2015 and 2,197 visits (from 86 countries) in 2016. This is similar to the statistics of access to BVID, which show 915 visits (from 60 countries) in 2015 and 1,200 visits (from 79 countries) in 2016. As for dissemination, also to be mentioned is a presentation about VGOS by Patrick Charlot at a French workshop on millimeter geodesy [8].

[2] The IVS Live Web site may be accessed at http://ivslive.obs.u-bordeaux1.fr.

6 Future Plans

Our plans for the next two years will be focused at first on implementing an operational analysis of the IVS-R1 and IVS-R4 sessions with the GINS software package. This implies validating the quality of the results derived with GINS, hence requiring further comparisons with other VLBI software packages, and demonstrating that we can sustain such operations in the long-term. Imaging the RDV sessions and evaluating the astrometric suitability of the sources, a specificity of the Bordeaux group, will be continued along the same lines. Of importance for the dissemination of the corresponding products is the reshaping of BVID with a new graphical interface and more functionalities, which is planned in the short term. The realization of the ICRF3 and its adoption by the IAU at the next General Assembly in the summer of 2018 will be crucial for the community. Our contributions to this effort lie mostly with the evaluation of the astrometric suitability of the sources, a task that is essential for selecting defining sources, and with the identification of proper Gaia transfer sources through dedicated observing programs or based on existing IVS data. Finalization of the list of such proposed Gaia transfer sources should be accomplished shortly. Organizing the overall work through face-to-face meetings and teleconferences falls to the Chair of the Working Group, who is a member of the Bordeaux group. Dissemination will include presenting ICRF3 at various meetings, preparing documentation and IAU resolutions, and writing a referred paper.

Acknowledgements

We would like to thank the OASU for supporting IVS activities in Bordeaux and the *Action Spécifique GRAM (Gravitation, Références, Astronomie, Métrologie)* of the CNRS for supporting ICRF3 activities.

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BKG/DGFI-TUM Combination Center Biennial Report 2015+2016

Sabine Bachmann [1], Linda Messerschmitt [1], Ralf Schmid [2], Mathis Bloßfeld [2], Daniela Thaller [1]

Abstract This report summarizes the activities of the BKG/DGFI-TUM Combination Center in 2015 and 2016 and outlines the planned activities for 2017 and 2018. The main focus in 2015 and 2016 was submitting the IVS contribution to the ITRF2014, adding source positions to the combination procedure, and investigating the potential of a consistently combined TRF/CRF solution. Furthermore, we included additional Analysis Centers into the combined solution. In 2017 and 2018, we intend to improve the combination strategy for small station networks, to expand the consistent realization for EOP, and to evaluate the impact of the different ITRS realizations (DTRF2014, ITRF2014, and JTRF2014) on the combined EOP.

1 General Information

The BKG/DGFI-TUM Combination Center was established in October 2008 as a joint effort of the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, or BKG) and the German Geodetic Research Institute (Deutsches Geodätisches Forschungsinstitut, or DGFI). The participating institutions as well as the tasks and the structure of the IVS Combination Center are described in [8]. The tasks comprise quality control and a timely combination of the session-based intermediate results of the IVS Analysis Centers (ACs) into a final combination product (e.g., Earth orientation parameters, or EOP). In coordination with the IVS Analysis Coordinator, the combination results are released as official IVS products. The Combination Center is also expected to contribute to the generation of the official IVS input to any ITRF activities.

The BKG/DGFI-TUM Combination Center performs a combination of session-based results of the IVS ACs on an operational basis. The strategy for the combination is based on the combination of normal equations and was adopted from the combination process as developed and performed by the IVS Analysis Coordinator (cf. [6], [7]).

At BKG, the following tasks are performed:

- Quality control of the AC results: checking the format of the results and their suitability for combination; identification and reduction of outliers; comparison of the Analysis Centers' results with each other, and comparison of the results with external time series provided by the IERS and IGS.
- Feedback to the Analysis Centers: quality control results are available at the BKG IVS Combination Center Web pages [5].
- Generation of high-quality combination products and timely archiving and distribution: combination products are created by using the combination part DOGS-CS of DGFI-TUM's software package DOGS (DGFI orbit and geodetic parameter estimation software) [3].
- Submission of official IVS combination products to the IERS: the products are submitted to the responsible IERS components to be used for IERS product generation (e.g., for EOP rapid products and the EOP series IERS C04).
- Generation of the official IVS input to the ITRF: the combined session products (from 1984 to present)

1. Federal Agency for Cartography and Geodesy (BKG)
2. Technische Universität München, Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)

BKG/DGFI-TUM Combination Center

IVS 2015+2016 Biennial Report

are submitted for ITRF computation in the form of normal equations in SINEX format. This work is also supported by the staff of the IERS Central Bureau hosted by BKG.
- Final results are archived in the BKG Data Center and mirrored to the IVS Data Centers at Observatoire de Paris (OPAR) and Goddard Space Flight Center (GSFC). This work is assisted by the staff of the BKG Data Center in Leipzig.

DGFI-TUM is in charge of the following Combination Center functions:

- DGFI is developing state-of-the-art combination procedures. This work, as well as the following item, is related to the ITRS Combination Center at DGFI and DGFI's efforts within the IERS WG on Combination at the Observation Level (COL).
- The software DOGS-CS is updated by implementing and documenting the developed state-of-the-art combination procedures.
- Adhering to IERS Conventions: the DGFI DOGS software package is continuously updated to be in accordance with the IERS Conventions.

2 Activities during the Past Years

At BKG, the following activities were performed in 2015 and 2016:

- Generation of a combined solution for IVS 24-h rapid sessions twice a week.
- Generation of a combined long-term solution of IVS 24-h sessions every three months.
- Ensuring that the combination process is in agreement with the IERS2010 Conventions.
- Generation of the IVS combined contribution to the ITRF2014 for the IERS ITRS Combination Centers.
- Inclusion of new ACs: Centro di Geodesia Spaziale (CGS), Italy and German Research Center for Geosciences (GFZ) into the routine rapid combination.
- Refinements of the combination procedure and implementation of source position combination.

The IVS contribution to the ITRF2014 was finalized and submitted to the IERS ITRS Combination Centers in February 2015. Figure 1 shows the VLBI station participation of the ITRF2014 submission. Overall 158 different stations observed between 1979 and 2015. The sessions on the right side of the vertical (red) line represent additional data collected since ITRF2008. Here, only stations with more than ten observations are shown. Figure 2 shows the WRMS over all stations for the combined and the individual solutions. Slightly improved statistics for the combined solution are visible for all components.

Figure 3 shows the scale of single combined sessions with respect to DTRF2008 (blue), ITRF2008 (red), and VTRF2014 (black). The VTRF2014 is a TRF which is generated from the AC submissions for the ITRF2014. An average scale offset of 0.3 ppb between DTRF2008/VTRF2014 and the ITRF2008 can be detected. Furthermore, two peculiarities around 2004 and 2014 with scale variations of about -0.6 ppb are evident. The corresponding periods contain many regional sessions with an unfavorable global station distribution for scale determination. This effect nearly vanishes if only R1 and R4 sessions are used for this comparison. We expect that improving the combination strategy for small networks will lead to a better understanding of scale variations with respect to the other space-geodetic techniques.

The combination procedure, as well as results for station coordinates and EOP, have been summarized in [1].

Source parameters have been added to the routine combination procedure. First tests show that source positions can benefit from a combined solution in a way similar to EOP and station coordinates in terms of, e.g., improved statistics. The objective is a consistent estimation of terrestrial and celestial reference frames and EOP in the near future. For our studies, we estimated a combined TRF/CRF containing 67 stations and 907 sources (including 291 ICRF2 defining sources). The resulting rotation angles A_1, A_2, and A_3 relative to ICRF2 are -12.7, 51.7, and 1.8 μas, the drifts D_α and D_δ are -67.2 and 19.1 μas/rad, and the bias B_δ is 26.1 μas. A comparison of the TRF solution with the IVS routinely combined quarterly TRF solution shows that the consistent estimation of the CRF has no significant impact on the TRF. The root mean square value of the post-fit station coordinate residuals is 0.9 cm. A detailed description was published in [2].

Concerning the operational rapid combination, contributions of two additional ACs were added. CGS using Calc/(nu)Solve and GFZ using VieVS@GFZ were introduced in the combination routine. This

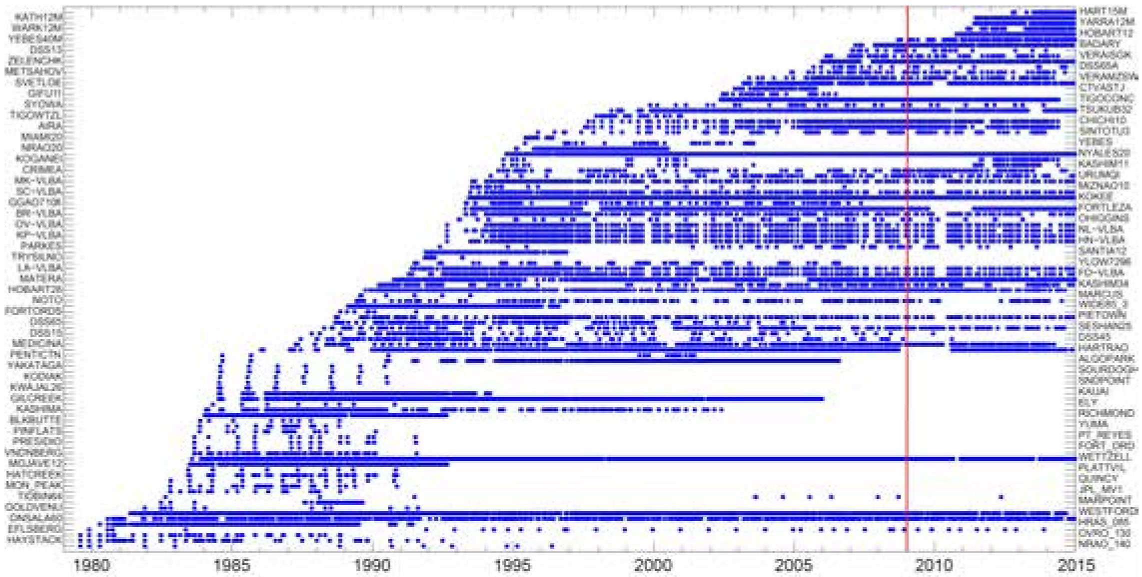

Fig. 1 VLBI station participation for ITRF2014. Only stations with more than ten observed sessions are shown, resulting in 158 different stations. On the right side of the vertical (red) line, additional sessions are shown that were not considered for the previous ITRF2008.

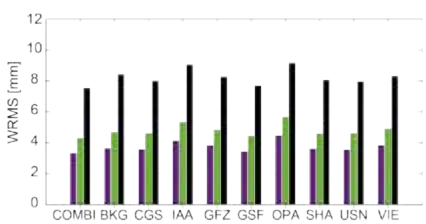

Fig. 2 Station coordinate WRMS of all stations in North (purple, left bar), East (green, middle bar), and Up (black, right bar).

increases the number of regularly contributing ACs to eight.

In 2016, the IVS Combination Center (CCIVS) revised its Web site. A predefined content management system was implemented to standardize the CCIVS Web presence. New features such as combination protocols, an interactive observatory map (see Figure 4), and more combination details were added to the available information about station coordinates, EOP, baselines, and combination results. The implementation changed the system structure and improves the administrative handling. It simplifies the workflow and allows a fast intervention in the system procedure. Results of the combination are published automatically and updated regularly. The revised Web site is accessible at http://ccivs.bkg.bund.de.

At DGFI, the following activities were performed in 2015 and 2016:

- Construction and integration of restitution equations.
- Update of a similarity transformation program.

3 Staff

The list of the staff members of the BKG/DGFI-TUM Combination Center in 2015 and 2016 is given in Table 1.

More details about the IVS Combination Center at BKG can be found in an interview for the IVS Newsletter [4].

4 Current Status

By the end of 2016, eight IVS ACs (BKG, CGS, DGFI-TUM, GFZ, GSFC, IAA, OPA, and USNO) contributed regularly to the IVS combined rapid and

Table 1 Staff members of the BKG/DGFI-TUM Combination Center.

Name	Affiliation	Function	E-Mail
Sabine Bachmann	BKG	Combination procedure development	sabine.bachmann@bkg.bund.de
Linda Messerschmitt	BKG	Operational combination/Web site maintenance	linda.messerschmitt@bkg.bund.de
Mathis Bloßfeld	DGFI-TUM	Combination strategies	mathis.blossfeld@tum.de
Michael Gerstl	DGFI-TUM	Software maintenance	michael.gerstl@tum.de
Ralf Schmid	DGFI-TUM	Combination strategies	schmid@tum.de

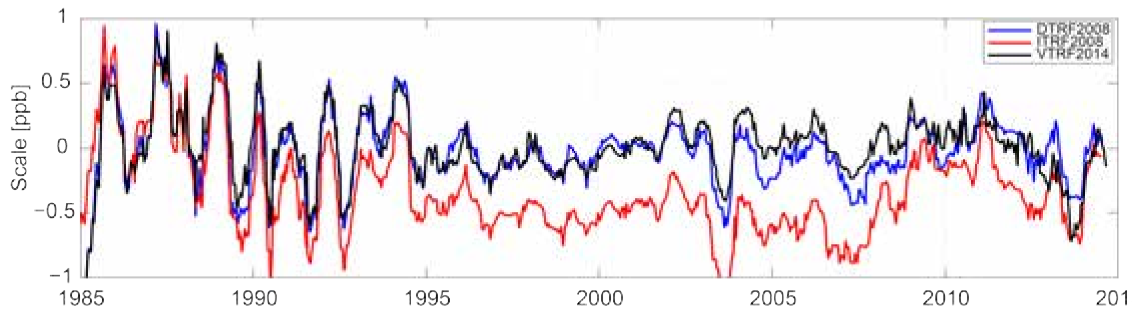

Fig. 3 Scale between single combined sessions and DTRF2008 (blue), ITRF2008 (red, bottom line) or VTRF2014 (black).

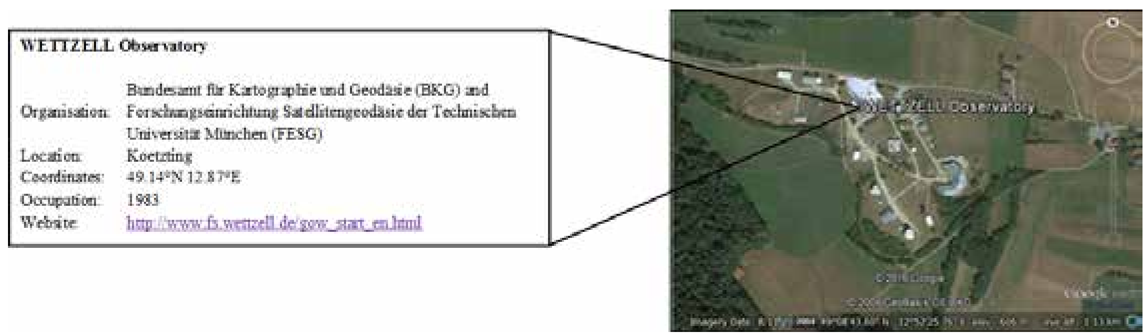

Fig. 4 Wettzell (Germany) as an example of the interactive map feature of the newly designed IVS Combination Center Web site.

quarterly product (see [5]). The AUS (Geoscience Australia) AC is currently under review and will probably become an IVS Operational AC in the near future. The rapid solutions only contain R1 and R4 sessions, and new data points are added twice a week as soon as the SINEX files of at least four IVS ACs are available. Long-term series are generated quarterly and include all 24-h sessions since 1984. The quarterly series include long-term EOP, station positions, and velocities. Furthermore, a VLBI TRF is generated and published. The software was extended to process source parameters for session-wise source combination as well as for a consistent generation of TRF and CRF. To prepare for the transition from ITRF2008 to the ITRF2014 reference frame, several tests of new software versions are in progress. The transition is planned for early 2017. The results of the combination process are archived by the BKG Data Center in Leipzig. The combined rapid EOP series, as well as the results of the quality control of the AC results, are also available directly at the BKG/DGFI-TUM Combination Center Web site [5] or via the IVS Analysis Coordinator Web site.

5 Future Plans

In 2017 and 2018, the work of the BKG/DGFI-TUM Combination Center will focus on the following aspects:

- Transition to ITRF2014 in the first months of 2017.
- Investigating the impact of different ITRS realizations (DTRF2014, ITRF2014, and JTRF2014) on the combined EOP.
- Extending the number of sources and the number of stations in the consistent TRF/CRF generation, as well as including EOP.
- Including new ACs into the routine rapid and quarterly combination.
- Improving the combination strategy for small station networks to increase their contribution to the EOP.

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Matera CGS VLBI Analysis Center

Roberto Lanotte [1], Simona Di Tomaso [1], Giuseppe Bianco [2]

Abstract This paper reports the VLBI data analysis activities at the Space Geodesy Center (CGS) of the Italian Space Agency (ASI) in Matera, from January 2015 through December 2016, and the contributions that the CGS intends to provide for the future as an IVS Analysis Center.

1 General Information

The CGS VLBI Analysis Center is located at the Matera VLBI station close to the town of Matera in the middle south of Italy. The Matera VLBI station became operational at the ASI/CGS in May 1990. Since then, it has been active in the framework of the most important international programs. The CGS, operated by E-GEOS S.p.A. (an ASI/Telespazio company) under an ASI contract, provides full scientific and operational support using the main space geodetic techniques: VLBI, SLR, and GPS. The work presented in this report is carried out by the E-GEOS staff consisting of Roberto Lanotte and Simona Di Tomaso.

2 Activities during the Past Two Years

During 2015–2016, the following activities were performed at CGS:

1. E-GEOS S.p.A., Centro di Geodesia Spaziale
2. Italian Space Agency, Centro di Geodesia Spaziale

CGS Analysis Center

IVS 2015+2016 Biennial Report

- Global VLBI Solutions asi2015a and asi2016a
  In these years we continued the annual realization of global VLBI solutions. The solutions are named asi2015a and 2016a and were realized using the CALC/SOLVE software developed at NASA/GSFC. The main and final characteristics of them are:

  asi2015a:

  - Data span: 1984.01.04–2014.12.29 for a total of 4,710 sessions
  - Estimated Parameters:
    - Celestial Frame: Right ascension and declination as global parameters for 944 sources,
    - Terrestrial Frame: Coordinates and velocities for 99 stations as global parameters, and
    - Earth Orientation: X pole, Y pole, UT1, Xp rate, Yp rate, UT1 rate, dX, and dY.

  asi2016a:

  - Data span: 1984.01.04–2015.12.29 for a total of 4,995 sessions
  - Estimated Parameters:
    - Celestial Frame: Right ascension and declination as global parameters for 1,368 sources,
    - Terrestrial Frame: Coordinates and velocities for 105 stations as global parameters, and
    - Earth Orientation: X pole, Y pole, UT1, Xp rate, Yp rate, UT1 rate, dX, and dY.

- IVS Tropospheric Products
  Regular submission of tropospheric parameters (wet and total zenith path delays and east and north horizontal gradients) for all VLBI stations observing in the IVS R1 and R4 sessions continued

during 2015–2016. Currently, 1,590 sessions have been analyzed and submitted, covering the period from 2002 to 2016. The results are available at the IVS products ftp site.

- Daily Solution Files (DSNX)
  Regular submission of daily sinex files for the IVS project "Daily EOP + station-coordinates solutions" continued during 2015–2016. All sessions lasting at least 18 hours were analyzed, and at present about 5,200 sessions have been submitted to IVS.
- Software development
  We continued the development of the software "*resolve*". The main goal of this software is the visual editing of a VLBI database. One of the reasons that led us to the development of this software was to have the capability to work on the output obtained from a run of SOLVE in BATCH mode. At present we have used *resolve* to edit approximately 60% of the databases of the daily Sinex production.

2.1 Staff at CGS Contributing to the IVS Analysis Center

- Dr. Giuseppe Bianco, responsible for CGS/ASI (primary scientific/technical contact).
- Dr. Rosa Pacione, responsible for scientific activities, E-GEOS.
- Dr. Roberto Lanotte, geodynamics data analyst, E-GEOS.
- Dr. Simona Di Tomaso, geodynamics data analyst, E-GEOS.

3 Future Plans

- Continue and improve the realization of our global VLBI solution, providing its regular update on time.
- Continue to participate in the IVS analysis projects.

DGFI-TUM Analysis Center Biennial Report 2015+2016

Ralf Schmid, Michael Gerstl, Younghee Kwak, Manuela Seitz, Detlef Angermann

Abstract This report presents the activities of the DGFI-TUM Analysis Center in 2015 and 2016. Besides regular IVS submissions, DGFI-TUM continued to reprocess 24-hour sessions including the estimation of source positions. DOGS-RI, the new VLBI analysis software to be used at DGFI-TUM, exhibited promising results in the VLBI Analysis Software Comparison Campaign 2015 (VASCC2015). First analyses of DOGS-RI SINEX files by the IVS Combination Center revealed a reasonable agreement with the IVS combined solution for recent sessions. Before switching to the new software, a long-term solution has to be analyzed.

1 General Information and Component Description

The DGFI-TUM Analysis Center (AC) is located at the German Geodetic Research Institute (Deutsches Geodätisches Forschungsinstitut der Technischen Universität München) in the city center of Munich in Germany. Having been an autonomous and independent research institution before, DGFI became an institute of the Technische Universität München (TUM) in January 2015 and is now called "DGFI-TUM".

Research performed at DGFI-TUM covers many different fields of geodesy (reference systems, satellite altimetry, Earth system modeling, etc.) and includes contributing to national and international scientific services and research projects as well as various functions in scientific organizations (see http://www.dgfi.tum.de).

DGFI-TUM has been acting as an IVS AC since the establishment of the IVS in 1999. Since November 2008, DGFI-TUM has been an operational AC regularly submitting constraint-free normal equations for 24-hour sessions in the SINEX format. Since 2008, DGFI-TUM has also been involved in the BKG/DGFI Combination Center.

Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM)

DGFI-TUM Analysis Center

IVS 2015+2016 Biennial Report

2 Staff

In May 2016, Younghee Kwak joined the DGFI-TUM AC to support the combined estimation of celestial and terrestrial reference frames (CRF/TRF).

Table 1 Staff members and their main areas of activity.

Dr. Detlef Angermann	Group leader
Dr. Michael Gerstl	Development of the analysis software DOGS-RI
Dr. Younghee Kwak	CRF/TRF combination, combination of different space geodetic techniques
Dr. Ralf Schmid	Routine data analysis, combination of different space geodetic techniques
Dr. Manuela Seitz (currently on maternity leave)	CRF/TRF combination, ICRF3, combination of different space geodetic techniques

Ralf Schmid has been taking care of the routine analysis of 24-hour sessions since the end of May

2013. In addition, Michael Gerstl is engaged in the development of a new VLBI analysis software called DOGS-RI (DGFI Orbit and Geodetic Parameter Estimation Software - Radio Interferometry). Table 1 lists the staff members and their main areas of activity.

3 Current Status and Activities

Analysis Activities

In 2015 and 2016, the DGFI-TUM AC continued to re-analyze 24-hour sessions including the estimation of source positions. Still using the analysis software OCCAM, the period from March 2003 to April 2008 could be covered. This means that, at the end of December 2016, consistent DGFI SINEX files (dgf2009a) were available from March 2003 to December 2016.

If operational and reprocessed solutions are summed up, DGFI-TUM analyzed 1,028 sessions altogether from twelve different years and submitted the corresponding daily SINEX files to the IVS. Among them were, e.g., 364 IVS-R4, 362 IVS-R1, 60 IVS-R&D, 60 VLBA, 47 IVS-T2, 35 IVS-OHIG, 33 EUROPE, 15 CONT05, and the eight VCS-II sessions (see Table 2).

The reprocessed DGFI-TUM solutions as of January 2004 were considered for an analysis of combined source positions by the IVS Combination Center [1]. DGFI-TUM could demonstrate comparatively low WRMS values resulting from source position time series. This is probably due to the fact that sources with fewer than four observations in one session were not considered. Moreover, sources with large deviations from the a priori values or large standard deviations were also eliminated from the session-wise solutions.

Software Development

After several years of implementation, DOGS-RI is close to becoming operational. After detailed internal comparisons with OCCAM, DOGS-RI participated in the VLBI Analysis Software Comparison Campaign 2015 [2] on the basis of computed theoretical delays. DOGS-RI was among the six software packages that could achieve a sub-mm agreement in terms of RMS differences.

A set of SINEX files for sessions in 2016 generated by a new SINEX interface was provided to the IVS Combination Center. An initial nutation bias could be related to an inconsistency between the nutation parameters contained in the SINEX files of different ACs. Obviously, some ACs still provide the total nutation angles instead of corrections w.r.t. the a priori model. To avoid further confusion, DGFI-TUM SINEX files will contain zero a priori nutation values.

After the nutation problem was fixed, the session-wise DOGS-RI solutions showed a reasonable agreement with the IVS combined solution. To rule out systematic long-term effects, it is the intention to reprocess data back to 2003 using the OCCAM preprocessing options (clock breaks, excluded stations, excluded sources, outliers, etc.).

Consistent realization of CRF and TRF

For a consistent realization of CRF and TRF, DGFI-TUM prepared multi-year solutions of VLBI, GNSS, and SLR covering the period between 2005.0 and 2016.0 (11 years, see Table 3). The session-wise VLBI solutions were analyzed with OCCAM, and the global multi-year solution was generated with DOGS-CS. In the multi-year VLBI-only solution, a declination bias w.r.t. ICRF2 is visible for southern sources that could also be detected by other ACs (see Figure 1).

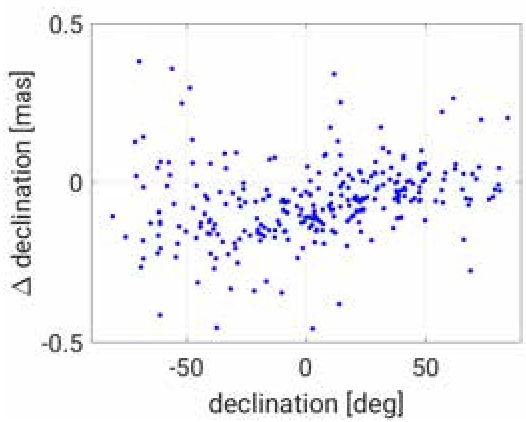

Fig. 1 Declination differences between the DGFI-TUM VLBI-only solution and the ICRF2 for defining sources.

Table 2 Sessions analyzed with OCCAM in 2015 and 2016.

Session type	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total
AOV	–	–	–	–	–	–	–	–	–	–	–	–	2	2	4
APSG	2	2	2	2	2	–	–	–	–	–	–	–	2	1	13
AUS	–	–	–	–	–	–	–	–	–	–	–	–	1	1	2
CONT05	–	–	15	–	–	–	–	–	–	–	–	–	–	–	15
EUROPE	3	3	3	6	6	–	–	–	–	–	–	1	6	5	33
IVS-CRF	3	1	2	1	2	–	–	–	–	–	–	–	–	3	12
IVS-E3	1	6	4	1	–	–	–	–	–	–	–	–	–	–	12
IVS-OHIG	–	2	3	6	7	3	–	–	–	–	–	6	6	2	35
IVS-R1	40	52	49	52	51	15	–	–	–	–	–	3	52	48	362
IVS-R4	39	51	50	51	52	15	1	–	–	–	1	8	52	44	364
IVS-R&D	8	4	10	10	9	3	–	–	–	–	1	6	6	3	60
IVS-T2	6	12	6	6	4	2	–	–	1	–	–	1	5	4	47
QUAKE	–	–	–	1	–	–	–	–	–	–	–	–	–	–	1
VCS-II	–	–	–	–	–	–	–	–	–	–	–	6	2	–	8
VLBA	7	11	13	8	7	2	–	–	–	–	–	1	6	5	60
Total	109	144	157	144	140	40	1	–	1	–	2	32	140	118	1028

Table 3 Multi-year (2005.0–2016.0) VLBI, GNSS, and SLR solutions.

	VLBI	GNSS	SLR
Institution	DGFI-TUM	CODE [3]	DGFI-TUM
Software	OCCAM	Bernese	DOGS-OC
Resolution	session-wise	daily	weekly
Datum conditions (station coordinates)	NNR/NNT	NNR/NNT/NNS	NNR
Datum conditions (source coordinates)	NNR	—	—
Coordinate jumps	according to DTRF2014 processing		

ICRF3

DGFI-TUM is represented in the IAU Working Group "Third Realization of International Celestial Reference Frame" (ICRF3) and intended for a combination of the ICRF3 solution from VLBI with GNSS and SLR. Although the ICRF3 solution resulting from a VLBI intra-technique combination is not ready yet, the combination strategy has already been prepared and tested. It mainly follows the procedure used for the consistent realization of CRF and TRF (see above).

4 Future Plans

In 2017, we intend to generate a DOGS-RI long-term solution. If the agreement with the IVS combined solution is satisfying, DGFI-TUM could switch from OCCAM to DOGS-RI. Besides, the inter-technique combination of VLBI, GNSS, and SLR for a consistent realization of CRF and TRF will be completed. As soon as a preliminary ICRF3 solution is available, we will combine it with other space geodetic techniques.

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GFZ Analysis Center 2015/2016 Biennial Report

Robert Heinkelmann [1], Tobias Nilsson [1], James M. Anderson [1], Kyriakos Balidakis [2], Santiago Belda [1,3], Georg Beyerle [1],Susanne Glaser [2], Maria Karbon [2], Li Liu [1,4], Sadegh Modiri [1], Julian A. Mora-Diaz [1], Chinh Nguyen Thai [1], Termitope Seun Oluwadare [1], Benedikt Soja [1,5], Minghui Xu [1,4], Harald Schuh [1,2]

Abstract This report briefly provides general information and the component description of the IVS Analysis Center at GFZ. Recent results are mentioned, and the planned future activities are outlined.

1 General Information

Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences is the national research center for Earth sciences in Germany. At this research facility, within Department 1 'Geodesy' and Section 1.1 'Space Geodetic Techniques', a VLBI group that is an associate Analysis Center (AC) of IVS has been established since the end of 2012.

2 Component Description

GFZ is an associate AC of IVS. We have installed and partly automatized our VLBI analysis process in preparation for becoming an operational AC. We are also performing as an IVS Combination Center for tropospheric products.

1. Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences
2. Technische Universität Berlin, Institute of Geodesy and Geoinformation Science, Chair of Satellite Geodesy
3. Department of Applied Mathematics, EPS, University of Alicante
4. Shanghai Astronomical Observatory, Chinese Academy of Sciences
5. Jet Propulsion Laboratory, California Institute of Technology

GFZ Analysis Center

IVS 2015+2016 Biennial Report

3 Staff

Since the 2014 Annual Report [1], Virginia Raposo-Pulido, Cuixian Lu, Minghui Xu, and Benedikt Soja have left the VLBI group, and we want to wish them the best of luck in their future careers. Additionally, we have had the pleasure of welcoming the following new colleagues to our group (in alphabetical order):

- Santiago Belda received his PhD at the University of Alicante, Spain, dealing with topics related to the EOP (Earth Orientation Parameters). During his studies he had two longer visits to GFZ, and after finishing his PhD he joined us as a PostDoc;
- Georg Beyerle, who previously worked in the GNSS group at GFZ, switched his topic to VLBI and joined our group;
- Sadegh Modiri joined us as a PhD student after finishing his MSc studies at University of Stuttgart, Germany. He is now investigating possibilities of applying Copula methods in VLBI analysis;
- Chinh Nguyen Thai, MSc, from Vietnam, is completing his PhD about the effects of ionospheric scintillations on GNSS and VLBI measurements; and
- Termitope Seun Oluwadare, MSc, from Nigeria, is completing his PhD about the investigation of ionospheric behavior over the African region.

The current members of the VLBI group and their functions are listed in Table 1, and a picture of us is displayed as Figure 1.

Table 1 Current members of the VLBI group at GFZ without MSc students.

Name	Main activity
Harald Schuh	Head of Department 1 at GFZ
Robert Heinkelmann	Head of VLBI group
Tobias Nilsson	Head of software development
James Anderson	Satellite observations, D-VLBI
Kyriakos Balidakis	Atmospheric effects
Santiago Belda	EOP
Georg Beyerle	Satellite simulations
Susanne Glaser	Combination of space techniques
Maria Karbon	CRF, Kalman filtering
Li Liu	Satellite observations
Sadegh Modiri	Copula-methods in VLBI analysis
Julian Mora-Diaz	CRF, source structure
Chinh Nguyen Thai	Ionospheric scintillations
Termitope Seun Oluwadare	Regional ionosphere

Fig. 1 A picture of GFZ VLBI group. Missing colleagues: Li Liu and Chinh Nguyen Thai.

4 Current Status and Activities

- **IVS Operational Analysis Center at GFZ**
We are currently in the test phase of becoming an operational IVS Analysis Center. Thus we are analyzing all R1 and R4 sessions and submitting our results to the IVS Combination Center within 24 hours after the version 4 database becomes available. We have set up scripts automating the downloading and analysis of new sessions as far as possible.
- **Contribution to ITRF2014**
We had the opportunity to evaluate the preliminary version of the ITRF2014, called ITRF2014P. We investigated the VLBI part, consulting baseline length repeatabilities, parameters of Helmert transformations, post-seismic deformation models, and Earth Orientation Parameters. ITRF2014P agrees on the mm-level with ITRF2008, and minor improvements in the VLBI analysis applying ITRF2014 can be expected [2].
- **VLBI Data Analysis using Kalman Filtering**
Within the project VLBI-Art[1] we have implemented a Kalman filter module in the GFZ version of the Vienna VLBI Software (VieVS@GFZ) [3]. The Kalman filter solution was thoroughly tested and the results compared to those from the standard least squares module (LSM) of VieVS@GFZ. We found that the results from the Kalman filter are generally as good as or better than those from LSM [3, 4, 5]. We have also made simulations testing the performance of the Kalman filter analyzing VGOS observations in real-time [6]. Furthermore, a Kalman filter for calculating TRF solutions from VLBI results was developed [7].
- **Space Applications**
The GFZ VLBI group contributes to the DFG Research Unit "Space-Time Reference Systems for Monitoring Global Change and for Precise Navigation in Space", funded by the German Research Foundation (FOR 1503), with the project "Ties between kinematic and dynamic reference frames (D-VLBI)"[2]. The D-VLBI technique (differential-VLBI, otherwise known as phase referencing) is being applied to geodetic observations of near-field spacecraft to demonstrate the potential of D-VLBI to directly tie spacecraft dynamic frames, including GNSS frames, to the celestial frame. Automatic D-VLBI scheduling software was developed, and initial test observations of GPS satellites and the Gaia spacecraft were performed. Simulations of D-VLBI and standard VLBI observations of various Earth-orbiting spacecraft have also been performed in order to estimate the ability of the D-VLBI and VLBI techniques to determine spacecraft orbital parameters, perform frame ties, and, for example, use VLBI observations to determine the Earth center of mass location in the terrestrial frame. These simulations have also contributed to the GRASP proposal to NASA and

1 http://www.gfz-potsdam.de/en/section/space-geodetic-techniques/projects/vlbi-art

2 http://www.gfz-potsdam.de/en/section/space-geodetic-techniques/projects/d-vlbi/

the E-GRASP/Eratosthenes proposal to ESA to put a geodetic reference spacecraft in orbit that could tie all four space geodetic techniques.

- **Simulation of a Global Terrestrial Reference System for GGOS**
  Within the DFG project GGOS-SIM[3] [8] we started with the simulation of the IVS-R1 and IVS-R4 sessions within the time span 2008–2014 of the current ground network [9]. The extension of the current VLBI network with single stations in Tahiti and Toro, Nigeria, results in improvements of the station positions of about 13% and of the Earth rotation parameters of about 14%. Simulations of VGOS station networks which are expected to be operational in five and ten years from now prove that the 1-mm GGOS requirement can be met with the VGOS station network in ten years. SLR observations were simulated as well, according to the accuracy and availability of real observations within the same time span. A combination of SLR and VLBI with known local ties (LT) shows that a combined solution using all LT with a standard deviation of 1 mm or better leads to the best datum realization [10]. In the framework of the important question of how to best assess the accuracy of global TRFs, a strategy for the velocity assessment of the global TRFs, called Velocity Decomposition Analysis (VEDA), was developed [11]. Furthermore, GPS and DORIS observations were simulated as well using consistent models and the same software. Further studies will include the combination of all four space geodetic techniques to provide reliable statements of a global TRF for GGOS.
- **Antenna axis offsets**
  The impact of antenna axis offsets in VLBI data analysis was studied in [12]. It was shown that if these are not correctly taken into account, it can cause significant errors in the VLBI results. Furthermore, we evaluated the possibility of estimating the axis offsets in the VLBI data analysis. This can be done with good precision for antennas with a long observation history, although in some cases the estimated values differ by several millimeters from those estimated in local surveys.
- **Climatological studies using VLBI** The homogenization and calibration of meteorological pressure, temperature, and relative humidity, as well as the estimation of long-term integrated water vapor trends, fall into this category. For the former, we have conducted extensive investigations using various meteorological data sources such as WMO sensors and multiple Numerical Weather Prediction Models (NWMs), to serve as a reference. We achieved the best VLBI analysis results when we employed homogenized meteorological data obtained using the model levels of ERA Interim reanalysis [13]. For the latter, we have modified the Theil-Sen estimator appropriately to robustly deduce integrated water vapor trends not only from VLBI, but from GNSS, ray-tracing, and direct numerical integration in NWMs.
- **Atmospheric refraction effects** We have created the Potsdam mapping functions as well as tropospheric gradients for 1st and 2nd order [14], employing the in-house ray-trace software DNS [15], based on the advanced mapping concept. We have confirmed their quality by analyzing VLBI observations with both the least-squares and Kalman filter models of VieVS@GFZ. Nevertheless, no matter how accurate the mapping function, the concept itself suffers from systematics stemming from its parametrized ansatz. Therefore, we are currently exploring the merits of employing ray-traced delays in VLBI analysis.
  We also performed a study where we compared tropospheric gradients estimated from DORIS, GNSS, VLBI, water vapor radiometers, and numerical weather models [16].
- **Geophysical loading effects** Crustal motion at a multitude of spatio-temporal scales is partly driven by mass redistribution occurring within the fluid envelope of the Earth. Developed at GFZ, geophysical loading models that simulate the displacements due to mass transport in the atmosphere, the oceans, and continental water storage[4] were extensively tested.
- **IVS tropospheric combination** The IVS tropospheric combination was relaunched. We provide

[3] http://www.earth.tu-berlin.de/menue/forschung/laufende_projekte/ggos_sim/parameter/en/

[4] ftp://ig2-dmz.gfz-potsdam.de/LOADING/

the combined tropospheric products in the latest Tropo-SINEX format [5].

- **Earth Orientation Parameters**
The consistency between the EOP and the celestial and terrestrial reference frames was investigated [17]. We found that the a priori TRF catalog used in the VLBI data analysis can have a significant impact on the estimated EOP values. We have also studied the Free Core Nutation (FCN) and derived a new empirical FCN model based on VLBI data [18].
- **Celestial Reference Frame**
We have contributed more than 5,800 SINEX files for the ICRF3 prototype solution. Furthermore, in view of ICRF3 and Gaia we aim to a maximal precision and accuracy for the VLBI-derived ICRF to allow an optimal link between the radio and optical catalogs and to improve the precision of all related astro-geodynamic quantities determined by VLBI, especially UT1 and nutation. We plan to achieve this goal through the extension of radio source coordinates. The multivariate adaptive regression splines (MARS) method was introduced in [19] to automatically model position variations of radio sources. This approach allows the elimination of systematics in the positions and consequently avoids any deterioration of other parameters by such effects. Through this method, the celestial pole offset (CPO) adjustments can be improved by more than 10%.
We have also done analysis of quasar source structure in geodetic analysis using the CONT14 dataset [20, 21]. Analysis of source structure and the effects of source structure on the geodetic observables and geodetic parameters through the analysis of closure quantities (closure delay, closure phase, and closure amplitude) was performed. ParselTongue scripts were written to automate the imaging of geodetic session observations, and images for all sources in the CONT14 campaign have been produced, both individually for each day in the campaign and combined over the entire 15 days. Analysis of the impact of the source structure determined from this analysis on the geodetic analysis is ongoing.

5 `http://kg6-dmz.gfz-potsdam.de/ivs/IVS-TROP-NEW/`

5 Future Plans

The following activities are planned for 2017–2018:

- Continuing our current investigations.
- Furthering the development of the software VieVS@GFZ. In particular, we want to implement the bandwidth synthesis ambiguities and ionospheric delay determination as part of our VieVS@GFZ version. Development is also foreseen for preparing the software for VGOS.

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BKG/IGGB VLBI Analysis Center

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Abstract In 2015 and 2016, the activities of the BKG/IGGB VLBI Analysis Center, as in previous years, consisted of routine computations of Earth orientation parameter (EOP) time series and of a number of research topics in geodetic VLBI. The VLBI group at BKG continued its regular submissions of time series of tropospheric parameters and the generation of daily SINEX (Solution INdependent EXchange format) files. Additionally a second series of daily SINEX files was generated with estimated source positions for all sources in each session. Quarterly updated solutions were computed to produce terrestrial reference frame (TRF) and celestial reference frame (CRF) realizations. The analysis of all *Intensive* sessions for UT1–UTC estimation was continued. All solutions are based on the Calc/Solve software, release 2014.02.21 [14], following the IERS2010 conventions. At IGGB, the emphasis was placed on individual research topics.

1 General Information

The BKG/IGGB VLBI Analysis Center was established jointly by the analysis groups of the Federal Agency for Cartography and Geodesy (BKG), Leipzig, and the Institute of Geodesy and Geoinformation of the University of Bonn (IGGB). Both institutions cooperate intensely in the field of geodetic VLBI. The responsibilities include both data analysis for generating IVS products and special investigations with the goal of increasing accuracy and reliability. BKG is responsible for the computation of time series of EOP and tropospheric parameters, for the generation of SINEX files for 24-hour VLBI sessions and one-hour *Intensive* sessions, and for the generation of quarterly updated global solutions for TRF and CRF realizations. Besides data analysis, the BKG group is also responsible for writing schedules for the Int2 UT1-UTC observing sessions. Details of the research topics of IGGB are listed in Section 3.

1. BKG
2. IGGB

BKG/IGGB Analysis Center

IVS 2015+2016 Biennial Report

2 Data Analysis at BKG

At BKG, the Mark 5 VLBI data analysis software system Calc/Solve, release 2014.02.21 [14], was used for VLBI data processing. It is running on a Linux operating system. Simultaneously first tests with the newly developed geodetic VLBI software *ν*Solve, a replacement of the interactive mode of Solve, have been realized. Calc/Solve allows the generation of so-called tropospheric path delay (TRP) files derived from the Vienna Mapping Function (VMF1) data. They contain external information about the troposphere on a scan-by-scan basis, specifically the a priori delay, dry and wet mapping functions, and gradient mapping functions. The BKG VLBI group uses TRP files to input data related to VMF1. The VMF1 data were downloaded daily from the server of the Vienna University of Technology. Additionally, the technological software environment for Calc/Solve was refined to link the Data Center management with the pre- and post-interactive parts of the EOP series production and to monitor all Analysis and Data Center activities.

- **Processing of correlator output**
  The BKG group continued the generation of calibrated databases for the sessions correlated at the Max Planck Institute for Radio Astronomy (MPIfR)/BKG Astro/Geo Correlator at Bonn (e.g., EURO, OHIG, and T2) and submitted them to the IVS Data Centers.
- **Scheduling**
  In cooperation with IGGB, BKG continued scheduling the Int2 *Intensive* sessions, which are observed on the TSUKUBA—WETTZELL baseline. Altogether, 204 schedule files for this baseline were created in 2015 and 2016. Due to the planned shutdown of the TSUKUBA antenna in 2017, the first schedule files for the ISHIOKA—WETTZELL baseline were also made available at the end of 2016.
- **BKG EOP time series**
  The BKG EOP time series bkg00014 was continued. The main features of this solution were not changed. But the station coordinates of the VLBI site HART15M in South Africa were estimated as global parameters because of an observation period of more than three years. Further, three new VLBI stations (ISHIOKA in Japan, RAEGYEB in Spain, and WETTZ13N in Germany) could be included successfully in data processing.
  Each time after the preprocessing of any new VLBI session (correlator output database version 1), a new global solution with 24-hour sessions since 1984 was computed, and the EOP time series bkg00014 was extracted. Altogether, 5,149 sessions were processed. The main parameter types in this solution were globally estimated station coordinates and velocities together with radio source positions. The datum definition was realized by applying no-net-rotation and no-net-translation conditions for 25 selected station positions and velocities with respect to VTRF2008a and a no-net-rotation condition for 295 defining sources with respect to ICRF2. The station coordinates of the telescopes AIRA (Japan), CHICHI10 (Japan), CTVASTJ (Canada), DSS13 (USA), ISHIOKA (Japan), KASHIM11 (Japan), KASHIM34 (Japan), KOGANEI (Japan), KUNMING (China), PT_REYES (USA), RAEGYEB (Spain), SEJONG (Korea), SEST (Chile), SINTOTU3 (Japan), TIANMA65 (China), TIDBIN64 (Australia), TIGOCONC (Chile), TSUKUB32 (Japan), UCHINOUR (Japan), VERAISGK (Japan), VERAMZSW (Japan), WETTZ13N (Germany), WIDE85_3 (USA), and YEBES40M (Spain) were estimated as local parameters in each session.
- **BKG UT1 *Intensive* time series**
  Regular analysis of the UT1-UTC *Intensive* time series bkgint14 was continued. The series bkgint14 was generated with fixed TRF (VTRF2008a) and fixed ICRF2. The a priori EOP were taken from final USNO series [16]. The estimated parameter types were only UT1-TAI, station clock, and zenith troposphere.
  The algorithms of the semi-automatic process for handling the *Intensive* sessions Int2/3 with station TSUKUBA after the Japan earthquake [3] were further used but refined by a newly developed extrapolation method; i.e., before the regular analysis can be started, the most probable station positions of TSUKUBA for the epochs of the Int2/3 sessions have to be estimated.
  A total of 5,722 UT1 *Intensive* sessions were analyzed for the period from 1999.01.01 to 2016.12.31.
- **Quarterly updated solutions for submission to IVS**
  In 2015 and 2016, quarterly updated solutions were computed for the IVS products TRF and CRF. There were no differences in the solution strategy compared to the continuously computed EOP time series bkg00014. The results of the radio source positions were submitted to IVS in IERS format. The TRF solution is available in SINEX format, version 2.1, and includes station coordinates, station velocities, and radio source coordinates together with the covariance matrix, information about constraints, and the decomposed normal matrix and vector.
- **Tropospheric parameters**
  The VLBI group of BKG continued regular submissions of long time series of tropospheric parameters to the IVS (wet and total zenith delays and horizontal gradients) for all VLBI sessions since 1984. The tropospheric parameters were extracted from the standard global solution bkg00014 and transformed into SINEX format.
- **Daily SINEX files**
  The VLBI group of BKG also continued regular submissions of daily SINEX files for all available 24-hour sessions for the IVS combined products

and for the IVS time series of baseline lengths. In addition to the global solutions, independent session solutions (bkg2014a) were computed for the station coordinates, radio source coordinates except for 295 defining sources of ICRF2, and EOP parameters including the X,Y-nutation parameters. The a priori datum for TRF was defined by the VTRF2008a, and ICRF2 was used for the a priori CRF information. A second series of daily SINEX files was generated with estimated source positions for all sources in each session as a basis for working on a combination procedure for CRF determination.

- **SINEX files for *Intensive* sessions**
  The generation of SINEX files for all *Intensive* sessions (bkg2014a) since 1999 was continued in 2015 and 2016. The parameter types are station coordinates, pole coordinates and their rates, and UT1-TAI and its rate. But only the normal equations stored in the SINEX files are important for further intra-technique combination or combination with other space geodetic techniques.

3 Research Topics at IGGB

- **ivg::ASCOT: Developement of a new VLBI software package**
  The VLBI group of IGGB started implementing a new analysis toolbox for VLBI observations. The main reason is the need for a flexible environment, which allows for straightforward implementations of new scientific and software-related ideas for VLBI data analysis. Furthermore, we wanted to accumulate the developments, which have been performed in Bonn in recent years, under a unified software package. The software is implemented in C++ and will finally be able to perform scheduling of VLBI sessions and simulation of VLBI observations, as well as geodetic data analysis and intra-technique combination. Thus, it is named: IGG VLBI Group – Analysis, Scheduling and Combination Toolbox (ivg::ASCOT, [1]). Currently, we are able to perform single-session data analysis from a stage where the ambiguities were resolved. For Intensive sessions we are already able to solve the ambiguities automatically. Furthermore, global solutions to derive celestial and terrestrial reference frames can be performed on the normal equation level. Intra-technique combinations of several solutions complete the initial functionality of the software package. Since the end of 2016, we have been able to generate schedules for Intensive sessions and small networks following different approaches for the selection of the next optimal source.
  Further information on ivg::ASCOT can be found at `http://ascot.geod.uni-bonn.de/`.

Fig. 1 Logo of the VLBI analysis software package ivg::ASCOT (IGG VLBI Group - Analysis, Scheduling and Combination Toolbox).

- **ivg::ASCOT: Scheduling and simulation**
  Within our newly developed software package we are able to schedule and simulate VLBI sessions. Our efforts here primarily concentrate on *Intensive* sessions with two or three telescopes and observing durations of only one hour. This is used in cooperation with BKG, and it will be used in 2017 to generate INT2 schedules. Here we focus on the approach of the automatic scheduling method based on the so-called impact factors [11]. This approach has been originally developed within a stand-alone software and is now successfully implemented in ivg::ASCOT. This transfer is also a consequence of the changeover from TSUKUBA-WETTZELL to ISHIOKA-WETTZELL and some issues within the legacy stand-alone scheduling program.
- **ivg::ASCOT: Using the intra-technique combination for CRF determination**
  Currently the third realization of the internationally adopted Celestial Reference Frame (CRF), the ICRF3, is under preparation. In this process, various optimizations are planned to realize a CRF. The new ICRF can benefit from an intra-technique combination as it is also done for the Terrestrial Reference Frame (TRF).
  Here, we aimed at estimating an optimized CRF by means of an intra-technique combination. The solu-

tions are based on the input to the official combined product of the IVS, also providing the radio source parameters. For this purpose, different strategies to improve the combined CRF were investigated and implemented in ivg::ASCOT.

- **ivg::ASCOT: Alternative estimation procedures for atmospheric parameters**
  Although the propagation delay due to the neutral atmosphere is referred to as a perturbation effect in the geodetic community, atmospheric refraction parameters become more and more important for other disciplines because the zenith wet delay (ZWD) estimates can be directly linked to the water vapor content in the atmosphere. However, the traditional model for the atmospheric delays sometimes leads to negative ZWD estimates, which, of course, do not reflect physical or meteorological conditions. To cope with this issue, an Inequality Constrained Least Squares (ICLS) adjustment from the field of convex optimization is used to force the ZWD estimates to non-negative values. Because deficiencies in the a priori hydrostatic modeling are almost fully compensated by the ZWD estimates, the ICLS urgently requires suitable a priori delays. Thus, different strategies to improve the a priori information have been investigated, and the impact of mis-modeling the a priori delay on station positions is shown in [6]. In general, the use of inequality constraints allows more suitable zenith wet delays in a meteorological sense and is possible without disturbing the VLBI target parameters. However, further investigations are necessary to validate other "dirt" effects which are compensated by the atmospheric delay estimates [6].
- **ivg::ASCOT: Modifying the stochastic model of VLBI observations**
  Microscale refractivity variations in the neutral atmosphere lead to elevation-dependent uncertainties and induce physical correlations between VLBI observations. Traditionally, such correlations are not considered in the stochastic model of VLBI observations, which leads to very optimistic standard deviations of the derived target parameters. Thus, a modified stochastic model based on a turbulence model was introduced to describe the dynamics in the atmosphere. One of the main objectives is to realize a suitable stochastic model, which can be used in an operational way. Up to now, it was shown that the new stochastic model leads to far more realistic standard deviations, and, further, the baseline length repeatabilities improve for a turbulence-based solution, particularly for specially designed local VLBI networks [5].
- **Observing the Chang'E-3 Lander with VLBI**
  In December 2013, a landing module was deployed on the Moon by China National Space Administration. In a project called OCEL (Observing the Chang'E-3 Lander with VLBI), a series of twelve observing sessions (four each in 2014, 2015, and 2016) was carried out with the IVS observing network. Part of the observing schedule was designed to observe the lander signal, which consists of five DOR (Differential One-way Ranging) tones. Fringe fitting and group delay determination are a particular challenge due to the fact that a new geodetic fringe fitting scheme needs to be developed to take care of narrow DOR tone spikes in a standard channel bandwidth of 4 or 8 MHz [7].
  At the same time multiple other activities are centered around the lunar observations concerning, for example, the near-field VLBI model and the parameter estimation module in ivg::ASCOT. In this context, the First International Workshop on VLBI Observations of Near-field Targets was held at the Institute of Geodesy and Geoinformation, University of Bonn, Bonn, Germany, on October 5—6, 2016 (`http://www3.mpifr-bonn.mpg.de/div/meetings/vonft/index.html`).
- **Studies on VLBI observations of Earth satellites**
  VLBI observations of Earth satellites are becoming important for geodesy in order to tie the terrestrial reference frame (TRF) to the celestial reference frame (CRF). However, VLBI observations of near-field targets are different from regular quasar observations in many respects, one major difference being that VLBI observations of near-field targets require special VLBI delay models, because the curvature of the observed wavefronts cannot be neglected as in the usual case of extragalactic radio sources (see [15]). We implemented two near-field VLBI delay models from the literature [12, 2] into the VLBI analysis software ivg::ASCOT. We tested our implementations by investigating the difference between the observed group delays and the computed VLBI delays, a quantity which is essential for further parameter estimation. Results for the VLBI observation of GPS satellites [8, 13] can be found in [10] and for the lunar lander Chang'E-3 in [4].

We are currently working on the development of a geometrical VLBI delay model optimized for Earth satellites. As a first application we are estimating the position of the lunar lander Chang'E-3 on the Moon.

- **Deformation measurements at radio telescopes**
  Another ongoing project is related to deformation measurements at radio telescopes. In November 2015, we visited the Onsala Space Observatory in Sweden and scanned the main reflector of the 20-m telescope with a terrestrial laser scanner (TLS). Difficulties arise from the fact that the surface is extremely accurate, almost like an optical mirror. As a consequence, the intensity of the reflections is extreme where the laser hits the surface perpendicularly, leading to inaccurate distance components of the TLS results. Nevertheless, some first results indicate that the focal length changes by close to 9 mm when tilting the telescope from zenith to 5 degrees elevation.

4 Personnel

Table 1 Personnel at the BKG/IGGB Analysis Center. The international code for all numbers is +49.

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GSFC VLBI Analysis Center Report

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Abstract This report presents the activities of the GSFC VLBI Analysis Center during 2015 and 2016. The GSFC VLBI Analysis Center analyzes all IVS sessions, makes regular IVS submissions of data and analysis products, and performs research and software development aimed at improving the VLBI technique.

1 Introduction

The GSFC VLBI Analysis Center is located at NASA's Goddard Space Flight Center in Greenbelt, Maryland. It is part of a larger VLBI group which also includes the IVS Coordinating Center, the CORE Operation Center, a Technology Development Center, and a VGOS station. The Analysis Center participates in all phases of geodetic and astrometric VLBI analysis, software development, and research. We provide several services and maintain several important data and information files for IVS and the larger geodetic community. These services include an atmospheric pressure loading service, a hydrology loading service, a nontidal ocean loading service, a ray tracing service, and an ECMWF meteorological data service. Data and information files include VMF1 TRP files for every IVS session, the IVS source name translation table, various station information files, a file of source and station a prioris needed for *Calc/Solve*, a mean gradients file, the JPL planetary ephemeris file needed for *Calc/Solve*, a source catalog, a source time series file, and several other files. These services and files can be found by following the 'Data/Results' link at our Web site, http://lupus.gsfc.nasa.gov, or from the Analysis Coordinator's Web site at http://lupus.gsfc.nasa.gov/IVS-AC_contact.htm.

1. NVI, Inc./NASA Goddard Space Flight Center
2. NASA Goddard Space Flight Center

2 Analysis Activities

The GSFC VLBI Analysis Center analyzes all IVS sessions using the *Calc/Solve/νSolve* systems, and performs the *fourfit* fringing and *Calc/Solve* analysis of the VLBA-correlated RV sessions. The group submitted the analyzed databases to IVS for all R1, RV, R&D, AUST, AUG, AOV, AUA, A14, A15, APSG, INT01, and INT03 sessions. During 2015/2016, GSFC analyzed 429 24-hour sessions (104 R1, 103 R4, 12 RV, 17 R&D, 27 AUST, 32 AUG, 12 AOV, 11 AUA, 17 A14, 30 A15, three APSG, 12 EURO, 12 T2, 14 OHIG, 14 CRF, and nine CRDS) and 765 one-hour UT1 sessions (465 INT01, 202 INT02, and 98 INT03), and we submitted updated EOP and daily Sinex files to IVS immediately following analysis. We also generated a contribution for the IVS combination solution for ITRF2014.

The GSFC group also released a new quarterly solution, 2016a, based on the latest released version of *Calc/Solve*. The solution uses the ITRF2014 apriori model and does not require estimation of TIGO-CONC or the Japanese stations' (e.g., TSUKUB32) post-seismic positions. Tests show that polar motion estimates agree better with GNSS than previous solutions that estimated these post-seismic positions. Also included in conjunction with the quarterly update are an astro source catalog and a source time series solution.

3 Research Activities

- ICRF3: Work towards ICRF3 by several members continued. The VCS-II VLBA observations were finished and the astrometric results were published. In eight VLBA sessions, 2,062 VCS sources were re-observed, resulting in an average improvement of 4.8 times in their position uncertainties, and 324 new sources were detected. Also, the RV sessions (VLBA + Mark IV stations) were used to observe and improve the positions of numerous weak sources. As of December 2016, the X/S catalog has 4,196 sources. Also, several new K-band sessions were analyzed and combined with earlier K-band sessions. D. Gordon generated preliminary ICRF3 source solutions at X/S and K bands and submitted them to the IAU's ICRF3 Working Group for comparisons and combinations by other WG members. The GSFC group also prepared for additional VLBA X/S reference frame observations in 2017 as part of the USNO's time allotment with the Long Baseline Observatory (LBO). And in preparation for ICRF3, K. LeBail studied methods using the Allan variance to select sets of sources that could define a stable celestial reference frame as well as identify the least stable sources that may need special handling.
- Galactic Aberration: D. MacMillan, as chair of the IVS Aberration Working Group (AWG), made several global solutions to estimate the solar acceleration vector. The estimates for the component of this vector towards the galactic center are close to those based on parallax measurements. However, the vector direction is generally $\sim 17^\circ$ north of the galactic center. Global estimates from other AWG members (M. Xu [Shanghai Observatory], H. Krásná [TU Wien]) also show a similar difference in the direction. The only AWG solution (O. Titov [Geoscience Australia] and S. Lambert [Paris Observatory]) that does not have this discrepancy used proper motions derived from source position time series. We are currently investigating this type of solution. An important goal of the AWG is to recommend an aberration model to the ICRF3 WG.
- Source Monitoring: The source monitoring program continued, with yearly targets of 12 sessions for geodetic sources, five for non-geodetic ICRF2 defining sources, six for ICFR2 special handling sources, and 12 for ICRF-Gaia transfer sources. A new category was also added, sources not observed since ICRF2, with a target of one session per year. An initial 100 (out of 500) of these were placed in the monitoring group. Some 255 more will be added in 2017, 190 of them being southern sources. We are working with the University of Tasmania to have these southern sources scheduled in Austral sessions. As for the group of 195 ICRF-Gaia transfer sources proposed by Bordeaux Observatory, their position uncertainties continued improving, reaching 50 μas or better for 90% of them. However, 33 are too weak or under-observed to be automatically scheduled in regular sessions, so they were scheduled in several RV sessions and in 12 dedicated R&D sessions. This work was described in a paper in the Astronomical Journal.
- UT1 Intensives: Numerous work was done to study ways to improve the Intensive schedules and UT1 estimates by K. Baver and J. Gipson. The 'Numerical Recipes Conjugate Gradient' method was used to identify ways to minimize the UT1 formal error, and generally selected observations near the cusps of mutual visibility between KOKEE and WETTZELL. Test versions of *sked* were developed to more evenly distribute the observations or place them in areas identified as likely to minimize the UT1 formal error. In late 2016, two R&D sessions were run in which one network of six stations observed a normal 24-hour schedule, and the Kokee–Wettzell network observed a sequence of 24 one-hour Intensive-like schedules in order to study a 50 source scheduling strategy. And research into the use of Bayesian estimation in INT01 analysis was begun. K. Baver also conducted scheduling simulations for VGOS broadband Intensive sessions for the KOKEE12M–WETTZ13S baseline, which show reductions in the UT1 formal errors compared to the current X/S KOKEE–WETTZELL schedules.
- *Solve*/*VieVS* UT1 Comparisons: K. Baver and J. Gipson worked with lead M. Uunila (Metsähovi Observatory), T. Nilsson (GFZ), and H. Krásná (TU Wien) to compare the *VieVS* and *Solve* software packages' estimates of UT1 for Intensive, R1, and R4 sessions. The results were published online in late December 2016 by the Journal of Geodesy and Geoinformation.

- Impact of a priori Errors on UT1 Estimates: J. Gipson and summer interns of 2015 A. Azhirnian and I. Strandberg investigated the impact of a priori modeling errors on the UT1 estimates from the IVS INT01 sessions. They did this by modifying the 'O-C' delays to introduce an error in one of the a priori models and then evaluating what the effect was on the estimated UT1 value. They studied the effects of changes to the coordinates of the Kokee and Wettzell stations, a priori zenith delays, east/west and north/south gradients at Kokee and Wettzell, polar motion, and nutation psi and epsilon. They found that the largest changes in UT1 (roughly in decreasing order) would result from changes to nutation psi or epsilon, changes to the East topocentric station coordinate of either station, and the use of a non-zero east/west gradient. Changes to the topocentric Up or North station positions had little effect, as did changes to the north/south gradients. This work was presented at the AGU 2015 Fall Meeting.
- Impact of the VLBA: The impact of the VLBA[1] on VLBI reference frames and EOP was studied by D. Gordon and published online in the Journal of Geodesy. It was found that ∼71% of the sources in the current X/S catalog were observed exclusively in VLBA geodetic/astrometric sessions. And for 790 sources observed in both VLBA and non-VLBA sessions, source precisions are significantly improved by the VLBA observations. The TRF is also significantly improved by inclusion of the VLBA sessions and the RDVs have produced the most accurate EOPs of any of the long-term session types.
- Simulation of Future GGOS Networks: D. MacMillan collaborated with UMBC colleagues E. Pavlis, M. Kuzmicz-Cieslak, and D. Koenig on simulations of expected future VLBI and SLR networks in five to ten years in order to assess their performance. These networks are being designed to meet the GGOS terrrestrial reference frame goals of 1 mm in accuracy and 0.1 mm/yr in stability. VLBI input was generated to the *Geodyn* combination software that was then used to do the VLBI+SLR TRF combination solutions. The VLBI input included VLBI parameter setup information and simulated delays for broadband networks of 17 and 27 stations. The simulations indicated that the scale, origin, and orientation accuracies will be at the level of 0.02 ppb, 0.4 mm and 16 µas. Additional simulations will be required to determine whether the GGOS stability requirements will be met.
- EOP and TRF Scale from Continuous Observing: D. MacMillan investigated the precision of EOP and the TRF scale from the CONT campaigns. The CONT precision is 2–3 times better than that of the operational weekly R1 and R4 sessions, most likely because the same network was used throughout each CONT campaign and the CONT networks were generally larger. Comparison of VLBI and GNSS polar motion shows that the precision from CONT11 and CONT14 is better than 30 µas, which is approaching the level of GNSS precision. Scale precision is 0.2 ppb. Simulations of future large broadband VLBI networks show that EOP and scale precision should improve by a factor of 2–3 over CONT precisions to about 12 µas for polar motion, 0.7 µsec for UT1 and 0.1 ppb for scale. A paper submitted to the Journal of Geodesy will be published in 2017.
- Comparison of VLBI, SLR, and GNSS Polar Motion: D. MacMillan compared polar motion series from the three independent geodetic techniques (VLBI, GNSS, and SLR) with the goal of 1) determining biases between the techniques, 2) determining the precisions of each technique by three-corner hat analysis, and 3) evaluating the long-term stability of the polar motion series. He found inter-technique bias peak-to-peak variations of 20–60 µas. He also found a systematic increase in the VLBI–GNSS polar motion differences after 2013 which also seems to be present in SLR–GNSS differences. This implies that this systematic is due to GNSS, but further investigation is required to confirm this. Precision of the VLBI R1+R4 sessions varies from 40 to 90 µas, where an improved precision since 2011 is probably due to the larger networks being used. CONT14 X-pole and Y-pole precision is 24 and 28 µas, which is close to the level of GNSS precision.

[1] The VLBA is operated by the Long Baseline Observatory (formerly by the National Radio Astronomy Observatory), which is a facility of the National Science Foundation, and operated under cooperative agreement by Associated Universities, Inc.

4 Software Development

The GSFC VLBI Analysis Center develops and maintains the *Calc/Solve* analysis system, a package of ∼120 programs and 1.2 million lines of code. A new version was released in late 2016. New features of the release include 1) ability to use post-seismic deformation models from ITRF2014, 2) ability to use a priori positions and velocities at more than one epoch, which is needed in order to apply ITRF2014, 3) utilities to list vgosDB variables in a session, 4) new control file options to specify the vgosDB directory or to output vgosDB debug information, 5) improved generation of Sinex files by reducing memory requirements, and 6) ability to apply epochs for a priori clock models.

S. Bolotin continued development of the ν*Solve* and *vgosDB* software. ν*Solve* is now fully operational and can replace the legacy interactive *Solve* program. Recent work has focused on transitioning from the legacy database handler format to the vgosDB format. For this effort, several utilities were created. *vgosDbMake* converts fourfit output into vgosDB format. It will replace the *dbmake* utility. *vgosDbCalc* is the vgosDB version of *Calc11*. It replaces the old DBH input/output library with code that implements the vgosDB format. *vgosDbProcLog* extracts cable calibration readings and meteorological parameters from station log files and adds them to a VLBI session that is stored in vgosDB format. It will replace the legacy utilities *pwxcb* and *dbcal*. Numerical tests were performed to validate these utilities. These utilities as well as ν*Solve* are distributed in one package, called “nusolve” and available at: ftp://gemini.gsfc.nasa.gov/pub/misc/slb/.

Difxcalc: D. Gordon created the *difxcalc* program for use with the DiFX software correlator. It is a modified version of *Calc11* in which the Mark III database handler input and output sections were replaced with code to read and write out files used in the *difx* correlation processing stream. It is designed to replace the *Calc9.12* program for computing correlator delay models, which had to be run as an RPC server. *Difxcalc* also contains near-field delay models for correlating signals from objects within the solar system. *Difxcalc* was entered into the *difx* repository and will be updated and maintained by GFSC.

In 2016, three summer interns, L. Olandersson, S. Strandberg, and E. Thorsell, worked on improving interprocess communication in *Solve*. Currently, different parts of *Solve* communicate by having one subroutine write data to disk and another subroutine read it. This method is used because when *Solve* was initially written, it was written as many individual programs, and this was the only way to pass data at the time. The interns looked at several different new options for passing data: a) Unix pipes, b) shared memory, c) TCP/IP, and d) ZeroMQ (an interface designed for large numerical simulation projects). To investigate these options, they wrote two simple toy programs in Fortran, a main program and a helper program. The main program passed data to the helper using one of these mechanisms. The helper did some calculations and passed the results back to the main program. Of the various options, the fastest interface was TCP/IP followed by ZeroMQ. However, the software overhead for TCP/IP is much more complicated. When the interns implemented the ZeroMQ interface in *Solve*, they saw no reduction in time for the programs to run, and the effort was put on hold.

5 Staff

During 2015/2016, the Analysis Center staff consisted of one GSFC civil servant, Dr. Chopo Ma, and six NVI Inc. employees who work under contract to GSFC. Dr. Ma oversees the GSFC VLBI project for GSFC, is an IVS Directing Board member, and is also the IVS representative to the IERS. Dr. John Gipson is the GSFC VLBI Project Manager as well as the IVS Analysis Coordinator and an IVS Directing Board member. Table 1 lists the staff members and their main areas of activity. We also hosted five temporary summer interns from Chalmers University of Technology (Sweden): Armin Azhirnian and Ingrid Strandberg in 2015 and Lina Olandersson, Simon Strandberg, and Erik Thorsell in 2016.

6 Future Plans

Plans for the next year include ICRF2 maintenance, source monitoring, VLBA observations and other preparations for ICRF3, participation in VGOS development, continued development of ν*Solve* and the new

Table 1 Staff members and their main areas of activity.

Ms. Karen Baver	S/X Intensive analysis and improvement; VGOS Intensive simulations; software development; Web site development; IVS publications; quarterly Nuvel updates.
Dr. Sergei Bolotin	Database analysis, *νSolve* development, vgosDB development, IAU ICRF3 WG member.
Dr. John Gipson	Analysis coordination, high frequency EOP, parameter estimation, vgosDB development, station dependent noise, galactic aberration WG member.
Dr. David Gordon	Database analysis, RV analysis, ICRF3 WG member, astronomical source catalogs, VLBA observations, galactic aberration WG member, *calc/difxcalc* development, quarterly ITRF updates.
Dr. Karine Le Bail	Source monitoring, time series statistical analysis (EOP, nutation, source positions), database meteorological data analysis.
Dr. Chopo Ma	ICRF3, CRF/TRF/EOP, VGOS development, IAU ICRF3 WG member, galactic aberration WG member.
Dr. Daniel MacMillan	CRF/TRF/EOP, mass loading, antenna deformation, galactic aberration WG chairman, VGOS and SGP simulations, VLBI/SLR/GPS combinations.

vgosDB data format, and continued research aimed at improving the VLBI technique.

7 Publications

'Minimization of the UT1 Formal Error through a Minimization Algorithm', John Gipson and Karen Baver, in 'Proceedings of the 22nd Meeting of the EVGA', R. Haas and F. Colomer (editors), pages 230–234, 2015.

'Improvement of the IVS-INT01 sessions by source selection: development and evaluation of the maximal source strategy', John Gipson and Karen Baver, J. Geodesy, 90:287-303, 2016. DOI 10.1007/s00190-015-0873-6.

'Improvement of the IVS-INT01 Sessions through Bayesian Estimation', John Gipson and Karen Baver, in IVS 2016 General Meeting Proceedings, D. Behrend, K. D. Baver, K. L. Armstrong (editors), pages 229–233, NASA/CP-2016-219016, 2016.

'Revisiting the VLBA Calibrator Surveys, VCS-II', David Gordon, in 'Proceedings of the 22nd Meeting of the EVGA', Ponta Delgada, Azores, R. Haas and F. Colomer (editors), pages 198–200, 2015.

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'Generation of Global Geodetic Networks for GGOS', D. MacMillan, E. C. Pavlis M. Kuzmicz-Cieslak, and D. Koenig, IVS 2016 General Meeting Proceedings, D. Behrend, K. D. Baver, K. L. Armstrong (editors), NASA/CP-2016-219016, pages 73–77, 2016.

Haystack Observatory Analysis Center

Arthur Niell, Roger Cappallo, Brian Corey, Mike Titus, Chet Ruszczyk, Pedro Elosegui

Abstract Analysis activities at MIT Haystack Observatory are directed at improving the accuracy of geodetic measurements, whether these are from VLBI, GNSS, SLR, or any other technique. Analysis activities that are related specifically to technology development are reported elsewhere in this volume for the Haystack IVS Technology Development Center, although sometimes the distinction is not clear. Activities and results during the two-year period include the improvement and development of programs and procedures that are used in the analysis of VGOS data, and analysis both of the first extended series of VGOS measurements and of four sessions to determine the vector baseline between the KPGO 12-m and 20-m antennas.

1 Introduction

The past two years have seen the evolution of VGOS observing from one-hour sessions, intended primarily for developing the operational procedures for each session, to full 24-hour sessions involving three stations and four-station sessions for evaluating station performance. Contemporaneously, the correlation and post-correlation procedures have had to evolve to accommodate unanticipated conditions, largely to do with the interaction of the dispersive phase term (ionosphere) and less than optimal hardware characteristics.

MIT Haystack Observatory

Haystack Analysis Center

IVS 2015+2016 Biennial Report

In order to cope with the new observing conditions (much larger differences of TEC between stations and poor phase linearity across the full spanned RF) and with the increase in data quantity, the program *fourfit*, which extracts the delay and phase observables for each scan, was enhanced, and a new program, *fourphase*, was developed to automate one step in the generation of the coherently-combined dual-linear polarization data.

A crucial measurement for current geodetic VLBI systems is the delay on the line carrying the reference frequency to the phase calibration (phasecal) generator. Unfortunately, several of the new VGOS systems lack any Cable Delay Measurement System (CDMS), so a proxy delay based on the multitone phasecal delay has been developed as part of the effort to obtain the best accuracy from these systems.

The major analysis activity was the processing of thirteen sessions of VGOS observations using the 12-meter antenna at the Goddard Geophysical and Astronomical Observatory (GGAO) and the 18-meter Westford antenna at Haystack Observatory. These sessions provided the raw material that pointed out the need to develop many of the improvements described above, and the geodetic analysis verified the level of achievement.

2016 saw initial observations by four new VGOS antennas. The first to become operational was the 12-meter antenna at the Kokee Park Geophysical Observatory (KPGO) (Elosegui et al 2016). Test sessions with GGAO and Westford were initiated for the three other VGOS antennas at Ishioka, Japan, Wettzell, Germany (Wettzell-S), and Yebes, Spain, and the observations were analyzed to uncover problems at those sites in preparation for operations to begin in 2017.

To obtain the maximum benefit of the new VGOS systems, it is essential to tie their positions to the reference frame established by the decades of observations with the legacy S/X systems. Four sets of observations with the legacy 20-meter antenna and the new 12-meter VGOS antenna at KPGO were conducted and analyzed. These observations required the use of mixed-mode correlation of the Mark IV S/X recordings from the 20 meter and the Mark 6 broadband recordings from the 12 meter.

2 Post-Correlation Analysis

The program for estimating the delay and phase for each scan, *fourfit* (originally developed at Haystack as *frnge*), has been evolving since the earliest days of geodetic VLBI. With the implementation of the broadband systems for VGOS, a major upgrade was necessary to allow the simultaneous estimation of the group delay and the dispersive phase term due primarily to the ionosphere (dTEC). Adjustments to the algorithms for estimating the dispersive term were made both to reduce the execution time and to improve the robustness of the dTEC detection.

The program *fourphase* was developed to automate the calculation of the delay and phase differences between polarizations for each station. The application of *fourphase* to one or more strong sources from a session provides the control file for running fourfit on the full set of scans.

3 Antenna Polarization Stability

The differences in delay and phase between the two linear polarizations for each station were monitored from the earliest observations, and they have exhibited extraordinary stability, at the level of a few picoseconds of delay and ten degrees of phase over long periods of time. The delay difference appears to provide a parameter for monitoring otherwise undetectable changes that might have occurred in the broadband instrumentation.

4 Cable Delay Measurement Proxy

The multiple phasecal tones within a band provide a measure of the delay from maser to recorder, including the uplink path for the reference frequency to the phasecal. The uplink cable is subject to stresses from the motion of the antenna that result in changes in delay that, if left uncorrected, can introduce systematic offsets in the estimated geodetic parameters, such as station position. Because there is no CDMS for the GGAO 12 meter, and none is planned for the near future, procedures were developed to measure the azimuth and elevation dependence of the phasecal delay and to apply the results as corrections in the geodetic analysis. This technique can also be used for other systems that lack (at least temporarily) a needed CDMS, such as the 13.2-meter VGOS antennas at Wettzell.

The dependence of the phasecal multitone delay on azimuth for GGAO at one epoch is shown in Figure 1. The delay correction for a scan is obtained by interpolation of the median value to the azimuth of an observation. Because the delay changes due to both wear and environmental conditions, the orientation dependence is measured approximately monthly.

Because the cable delay value is such an essential component of the final geodetic estimation, the usage and accuracy are of interest as Analysis Center activities.

5 Geodetic Analysis

The vgosDb structure is used for the geodetic databases, which are created at Haystack from the data that were correlated and subsequently processed through *fourfit* using the *fourphase* results. The analysis is done with nuSolve, including the use of the appropriately formatted proxy cable delay file (see description in Niell et al., 2016). Both the vgosDb suite of programs and nuSolve are installed and in use at Haystack and will be run on all VGOS sessions processed there.

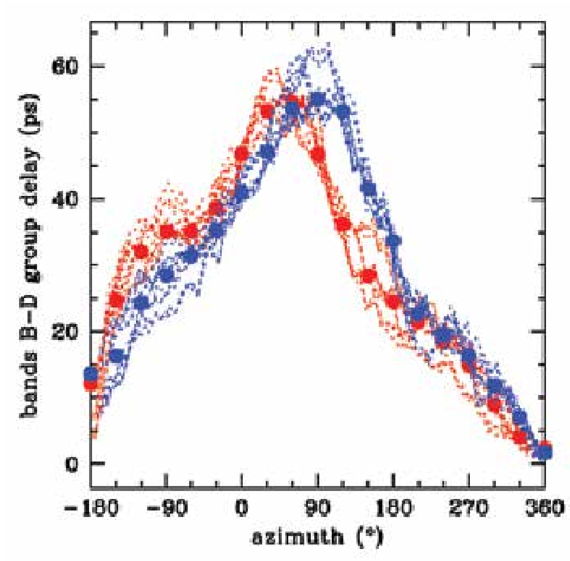

Fig. 1 GGAO12M phasecal multitone delay measurements as a function of azimuth with median values. The averages of the clockwise (blue) and counter-clockwise (red) values were used as nodes for piecewise linear interpolation in azimuth.

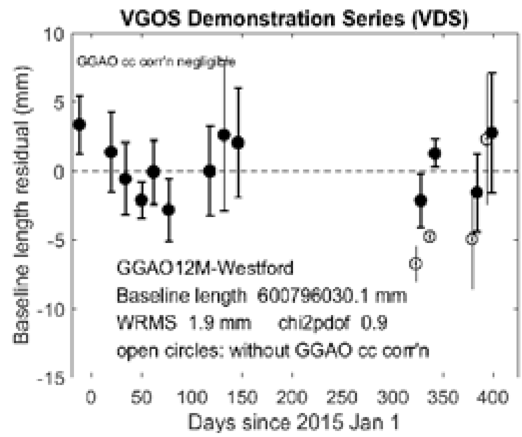

Fig. 2 Baseline length between GGAO12M and Westford VGOS antennas from 2014 December through 2016 February. Solid circles: either no cable delay correction at GGAO12M (first nine sessions) or with cable delay correction when azel dependence was significant (last four sessions). Open circles: length of baseline with no cable delay correction applied for GGAO. No cable delay correction was made for Westford.

5.1 GGAO12M-Westford VDS Sessions

As projected in the 2014 Haystack IVS Annual Report (Niell et al., 2015), the VGOS Demonstration Series (VDS) of primarily one-hour sessions was initiated in 2014 December. Thirteen sessions were successful through 2016 February. The sessions were scheduled, coordinated, correlated, and analyzed through to a geodetic solution by Haystack personnel. Due to lack of time, the proxy cable delay values for GGAO12M were applied to only the last four sessions. For the first nine sessions, the 5 MHz cable at GGAO showed less than a few picoseconds of variation with antenna orientation, so any correction in the baseline length is expected to be less than one millimeter. For the last four sessions, application of the proxy cable delay reduced both the WRMS scatter of the baseline lengths and the post-fit group delay residuals, supporting the validity of the proxy concept. As can be seen in Figure 2, the weighted RMS of the cable-delay-corrected length residuals is slightly less than 2 mm with a chi-squared per degree of freedom of about 1.

5.2 Kokee12m

A major milestone was reached during the past two years. The first operational VGOS system was completed at KPGO as a joint USNO/NASA/Haystack project, consisting of a commercial 12-meter antenna and a broadband signal chain designed and constructed by Haystack. As the developer of the signal chain, it was the responsibility of Haystack to validate the geodetic performance of the antenna and broadband receiver. Six validation sessions of six to 24 hours were conducted with GGAO12M and Westford. Only preliminary geodetic solutions have been completed.

Four sessions, ranging in length from one hour to 22 hours, were observed using the Kokee 12-meter and 20-meter antennas to obtain a VLBI tie of the 12-meter antenna's position to the 20-meter antenna. The broadband frequencies for the 12-meter antenna were changed from the standard VGOS values to provide overlap with the fixed frequencies of the 20-meter S/X Mark IV system. Both the S-band and X-band data were correlated on the DiFX correlator at Haystack using mixed-mode, but only the X-band data were analyzed, because the ionosphere difference between the antennas is negligible. After some modifications to *fourfit*, the four sessions yielded a three-dimensional local tie with a precision of approximately 1 mm.

6 Analysis Challenges

At this point (2017 January), implementation of the broadband delay capability that enables the VGOS concept still has several tasks that need development or understanding in order to attain an operational network.

- Work towards automation of the correlation and post-correlation processing of over 1,000 scans per session for each baseline.
- Improve the cable-delay proxy procedure and accuracy.
- Account for, and reduce, phase non-linearity across the bands.
- Understand the sampler delay *a priori* differences between bands for different cable types.
- Develop procedures for calculating correlated flux density by band.

7 Outlook

During the next biennium we will address the challenges of the previous section. In addition, the size of the VGOS network and the diversity of antenna systems will increase, and new challenges will certainly present themselves. Although not discussed explicitly, it is imperative to combine the VGOS and legacy networks in order to optimally incorporate the VGOS stations into the ITRF established by the legacy stations. The procedures for accomplishing this are not fully developed, although they are being worked on.

Acknowledgements

We thank the many people who have worked to implement the VGOS stations and bring them to operations.

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IAA VLBI Analysis Center 2015–2016 Biennial Report

Elena Skurikhina, Sergey Kurdubov, Vadim Gubanov, Svetlana Mironova

Abstract This report presents an overview of the IAA VLBI Analysis Center activities in 2015 and 2016 and our future plans.

1 General Information

The IAA IVS Analysis Center (IAA AC) operates in the Institute of Applied Astronomy of the Russian Academy of Sciences, St. Petersburg, Russia. The IAA AC contributes to IVS products, such as daily SINEX files, TRF- and CRF-solutions, rapid and long-term series of EOP and tropospheric parameters, which are obtained from the IVS observational sessions. The IAA AC also generates and submits to IVS NGS files transformed from Mark III DBH files.

Besides IVS VLBI data, IAA AC processes domestic observations produced by both the RT32 radio telescopes (Svetloe, Zelenchukskaya, and Badary) and the new RT13 new generation radio telescopes located at the Zelenchukskaya and Badary observatories.

2 Staff

- Sergey Kurdubov: development of the QUASAR software, global solutions, and DSNX file calculation.
- Prof. Vadim Gubanov: development of the QUASAR software and development of the methods of stochastic parameter estimation.
- Elena Skurikhina: team coordination; VLBI data processing, and OCCAM/GROSS software development.
- Svetlana Mironova, PhD Student: development of the QUASAR software, global solutions, and DSNX file calculation.

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IVS 2015+2016 Biennial Report

3 Activities during the Past Two Years

3.1 Routine Analysis

In 2015 and 2016, the IAA AC continued to generate daily SINEX (DSNX) files from analysis of IVS-R1 and IVS-R4 sessions using the QUASAR software. DSNX files are submitted to the IVS for combination with results from other Analysis Centers.

The IAA AC operationally processed the 24-hour and Intensive VLBI sessions using OCCAM/GROSS software and submitted the results to the IERS and the IVS on a regular basis. Processing of the Intensive sessions is fully automated.

Calculation of new EOP time series with ITRF2014 is performed.

3.2 Global Solution

A new global solution was calculated using all available IVS VLBI data from November 1979 to May 2016. A total of 7,877,714 delays were processed.

The CRF was fixed by NNR constraints to 212 radio sources. The TRF was fixed by NNR and NNT constraints to the station positions and velocities of 15 stations: BR-VLBA, FD-VLBA, FORTLEZA, HN-VLBA, KP-VLBA, LA-VLBA, MATERA, NL-VLBA, ALGOPARK, WESTFORD, WETTZELL, HARTRAO, KOKEE, NYALES20, and ONSALA60. Stochastic signals were estimated by means of the least-squares collocation technique. The radio source coordinates, station coordinates, and corresponding velocities were estimated as global parameters. EOP, WZD, troposphere gradients, and station clocks were considered as arc parameters for each session. The following 6,732 global parameters were determined: 3,258 source positions, the positions and the velocities of 117 VLBI stations, and 23 position and velocity discontinuities. A station position catalog containing 132 stations was calculated as well.

We prepared a new source position catalog, iaa-sx-161013-b.cat, as one of the catalogs that were created for the IERS/IVS ICRF3 Working Group. Differences between the coordinates of iaa-sx-161013-b.cat and ICRF2 are approximately at the same level as differences between other catalogs and ICRF2. Formal uncertainties in declination and right ascension of sources observed at least 100 times do not exceed 1 mas.

3.3 EOP Parameter Calculation from Domestic Observations

The IAA Analysis Center processes all observational data of domestic VLBI programs Ru-E, Ru-I, R, and test sessions. Table 1 presents the main types of Russian domestic sessions. The standard IVS designation of the stations is used in the table: Sv – Svetloe, Zc – Zelenchukskaya, and Bd – Badary for RT-32 and Bv – Badary and Zv – Zelenchukskaya for RT-13.

Observational data from all of these sessions are transmitted to the correlators using e-VLBI data transfer. The data of 24-hour sessions are shipped to the IAA correlator on disk modules only from the “Svetloe” observatory. The processing of Ru-I sessions is fully automated. A calculated UT1-UTC time series is available at ftp://quasar.ipa.nw.ru/pub/EOS/IAA/eopi-ru.dat. The EOP time series calculated from Ru-E data is available at ftp://quasar.ipa.nw.ru/pub/EOS/IAA/eops-ru.dat.

Table 1 Specifications of the Russian domestic sessions.

Program	Ru-I	Ru-E	R
Stations	BdZc(Sv)	SvZcBd	ZvBv
Duration, hours	1	24	0.5–1
Aim	dUT1	EOP	dUT1
Turn-around time	2 hours	3–5 days	2–6 hours
Schedule	daily 20:00 UT	weekly Fri 22:00 UT	3–7 times per day
Range	X/S	X/S	X/S
Scan duration, s	22–127	60	10
Sources set	150(>0.25 Jy)	60 (>0.5 Jy)	156
Num sources/sess	20	50	60
Sampling	1-bit	1-bit	2-bit
Bandwidth, MHz	8	8	512
Data rate, Mbit/s	256	256	2048
Number scans	25	300–350	120
Number obs.	25	1000	120
Correlator	IAA ARC	IAA ARC	RASFX, DiFX

In 2015 and 2016, 72 Ru-E and 735 Ru-U sessions were observed. The accuracy of EOPs estimated by the IAA AC from the analysis of these observations in comparison to the IERS EOP 14 C04 series for two years is presented in Table 2.

Table 2 RMS differences with respect to EOP IERS 14 C04.

EOP	N_{sess}	Bias	RMS
X_p, mas	72	−0.23	0.84
Y_p, mas	72	0.12	1.25
UT1-UTC, µs	72	15	44
X_c, mas	72	0.31	0.43
Y_c, mas	72	−0.09	0.45
UT1-UTC Int., µs	735	−0.07	43

In 2015–2016, the new Badary–Zelenchukskaya VGOS radio interferometer observed 1,515 one-hour sessions in the scope of the R domestic program. The UT1-UTC accuracy obtained from these observations is about 30 µs. Preliminary coordinates of the new RT-13 radio telescopes (ZELRT13V and BADRT13V) were estimated from test sessions with one baseline, and then the coordinates were improved using the series of 24-hour sessions that observed the five station network of SVETLOE, ZELENCHK, BADARY, ZELRT13V, and BADRT13V. The results are presented in Table 3. The following fixed velocity values have been used for the solution: $v_x = -0.0222$ m/year, $v_y = 0.0144$ m/year, and $v_z = 0.0092$ m/year for Zelenchukskaya and $v_x = -0.0281$ m/year, $v_y = 0.0009$ m/year, and $v_z = -0.0020$ m/year for Badary.

Table 3 RT-13 station positions at 2005.0 epoch.

Coordinate	Zelenchukskaya	Badary
X, m	3451257.503 ± 0.002	−838326.468 ± 0.002
Y, m	3060268.061 ± 0.002	3865797.199 ± 0.004
Z, m	4391933.124 ± 0.003	4987598.314 ± 0.007

3.4 Earth Tidal Deformation Study

Some investigations were made in the field of solid Earth tidal deformation at the limit of the capabilities of modern astronomical and geodetic observations. We obtained corrections to the theoretical values of frequency-dependent tidal parameters (Love/Shida numbers) from the analysis of all available IVS VLBI observations for the period 1980–2014. The frequency dependence of these parameters is caused by resonance effects due to Retrograde Free Core Nutation (RFCN). On the whole, our results confirm the high precision model of the Earth tides as it is represented in the modern international astronomical and geodetic standards IERS Conventions (2010). However, some harmonics of lunisolar tide generating potential are in significant disagreement. Thus, the estimate of the real part of Love number h for the K_1 harmonic with a frequency of 1 cycle per sidereal day (cpsd) equals $\Delta h^R = -0.0142 \pm 0.0006$. This may indicate the existence of a deeper resonance in the diurnal tides than it is predicted by the theory.

4 Current Status

The IAA AC processes the data of all kinds of VLBI geodetic observation sessions. We use the QUASAR and the OCCAM/GROSS softwares for VLBI data analysis. All observation models in these packages are compliant with the IERS Conventions (2010). Both packages use NGS files as input data.

The QUASAR and the OCCAM/GROSS software packages are supported and are being developed. Some modifications have been made to QUASAR. Memory allocation was changed from static to dynamic due to the number of delays having grown in single sessions. This makes it possible to use almost all of the memory system of a computer.

5 Future Plans

- To continue submitting all types of IVS product contributions.
- To continue investigations of EOP, station coordinates, and tropospheric parameter time series.
- To improve algorithms and software for processing VLBI observations.
- To contribute to the ICRF3 Working Group studies.

Italy INAF Analysis Center

Monia Negusini, Matteo Stagni, Pierguido Sarti

Abstract This report summarizes the activity of the Italian INAF VLBI Analysis Center. Our Analysis Center is located in Bologna, Italy and belongs to the Institute of Radio Astronomy (IRA), which is part of the National Institute of Astrophysics (INAF). IRA runs the observatories of Medicina and Noto, where two 32-m twin VLBI AZ-EL telescopes are located. This report contains the AC's VLBI data analysis activities and illustrates the latest experiments, involving the Italian antennas and correlator, carried out in the last two years.

1 Current Status and Activity

Following the installation of the software correlator DiFX in 2012 in Bologna, there have been a number of experiments to test the correlation pipeline for geodesy. These VLBI experiments were performed mainly on a single baseline Medicina — Noto and subsequently extended to Matera after seeking a collaboration with ASI, who manages the antenna facility. The VITA (ITAlian Vlbi network) project has been launched as a national pilot project, obtaining observing time at the stations. We obtained first successful fringes on the three baselines in April 2015 after some gaps in the availability of the antennas due to major maintenance and refurbishing during 2014.

Meanwhile there was also a major switch of the Medicina and Noto antennas to the DBBC2 systems, which have progressively become the standard backend for geodetic observations also on the IVS network. Medicina was changing from a Mark IV backend, while Noto was changing from a VLBA one. This required some hardware and software procedure adjustments at the antennas, the geodetic set up already being embedded in the DBBC, although the transition to the newer formatter Fila10G, designed to complement the DBBC, proved to be more difficult, particularly on the correlation side. In fact some time was required before SKED was updated to reflect the changes at the antennas and manual editing of vex files was no longer needed. Further adjustments were also implemented when the decision was taken to change to the VDIF format, which on one hand brings the advantage of more streamlined data transmission on the networks, but on the other still is not fully implemented in SKED.

After overcoming these initial challenges we were able to perform four successful experiments across 2015 and 2016 with the aim of setting up a calendar of regular experiments similar to EUROPE ones, but on a smaller scale. Additional work is needed to find the optimal scheduling set-up.

At present we are also involved in the LIFT project in collaboration with INRIM (National Institute of Metrology) where a distributed time and frequency optical link was set up in Medicina to perform multiple VLBI tests in a geodetic setup to verify the accuracy and reliability of their solution compared to standard maser clock timing in use at the antenna. During the EUR137 experiment in 2015, Medicina participated with both clock synchronizations, and afterwards a few more experiments on the Medicina — Noto baseline were performed to try to solve the issues raised. There were updates to the INRIM system in Medicina, so more experiments are expected in the near future.

Istituto di Radioastronomia INAF, Bologna

INAF Analysis Center

IVS 2015+2016 Biennial Report

In 2017 it is also planned to connect the Matera antenna to the distributed time and frequency link, thanks to the newly founded MeTGeSp project. Additional VITA experiments with the common clock, delivered by INRIM, will be performed as soon as the optical link will be available.

2 Data Analysis and Results

The IRA started to analyze VLBI geodetic databases in 1989, using a CALC/SOLVE package on the HP1000 at the Medicina station. In subsequent years, the same software was installed first on an HP360 workstation and later on an HP715/50 workstation. In more recent years, two HP785/B2600 workstations and an HP282 workstation were used. In 2007, a new Linux workstation was set up for the migration of all the VLBI data analysis, and Mark 5 Calc/Solve was installed. During the last years, our Analysis Center had some inner problems, and we did not participate regularly in IVS activities. But we continued to update the catalog, and we installed and tested the latest releases of CALC/SOLVE and νSolve.

3 Outlook

We expect that another researcher will join the group in the next few months, allowing us to contribute again to IVS activities and to submit INAF tropospheric parameters to the IVS Data Centers regularly. We will also produce an updated long term geodetic solution.

KTU-GEOD IVS Analysis Center Biennial Report (2015–2016)

Emine Tanır Kayıkçı [1], Kamil Teke [2], Özge Karaaslan [1], Mehmet Fikret Öcal [2]

Abstract This report summarizes the activities of the KTU-GEOD IVS Analysis Center (AC) in 2015 and 2016 and outlines the planned activities for the years 2017 and 2018. Estimating the parameter UT1-UTC from the observations of IVS [1] Intensive sessions with VieVS [2] and comparison of ITRF2014 [3] station coordinate input time series of VLBI [1], GNSS [4], and DORIS [5], are our specific interests for 2015 and 2016.

1 General Information

In 2016, two graduate students have been added to our group. They are Ms. Özge Karaaslan (PhD student) and Mr. Mehmet Fikret Öcal (MSc student). Ms. Özge Karaaslan will be working on the comparison of parameter estimation results in VLBI (Very Long Baseline Interferometry) data analysis performed by Kalman Filter (KF) and classical Least Squares Method (LSM). Mr. Mehmet Fikret Öcal will estimate UT1-UTC using Vienna VLBI Software, VieVS [2] to analyze the observations of the IVS Intensive sessions, and he will compare the VLBI results to those from GNSS, e.g. IGS [6]. A new Geodesy Lab was built up at Hacettepe University with the present capacity of analyzing VLBI and GNSS sessions using VieVS [2] and Bernese Software [7] running on a Linux (Ubuntu V14, LTS: Long Term Support) operating system. One of the targets of the Geodesy Lab at Hacettepe University is to support the KTU-GEOD IVS AC through close co-operation with the VIE AC at the Vienna University of Technology (TU Wien).

1. Karadeniz Technical University, Department of Geomatics Engineering
2. Hacettepe University, Department of Geomatics Engineering

2 Staff at KTU-GEOD Contributing to the IVS Analysis Center

Members of the KTU-GEOD IVS Analysis Center (AC) are listed in Table 1 (in alphabetical order) with their main focus of research and working location [8, 9]:

Table 1 Staff.

Name	Working Location	Main Focus of Research
Emine Tanır Kayıkçı	Karadeniz Technical Univ., Dept. of Geomatics Eng., Trabzon, Turkey	responsible person from AC, parameter combination
Kamil Teke	Hacettepe Univ., Dept. of Geomatics Eng., Ankara, Turkey	troposphere
Mehmet Fikret Öcal	Hacettepe Univ., Dept. of Geomatics Eng., Ankara, Turkey	data analysis, signal processing
Özge Karaaslan	Karadeniz Technical Univ., Dept. of Geomatics Eng., Trabzon, Turkey	data analysis, parameter estimation

Fig. 1 Members of the KTU-GEOD IVS Analysis Center (AC) participated in the Seventh VieVS [2] User Workshop, which was held in Vienna in 2016.

3 Current Status and Activities

During 2015 and 2016, we continued working on inter-technique comparisons of different parameters estimated from the observations of the satellite/space geodetic techniques, i.e., GNSS (Global Navigation Satellite Systems, [4]), VLBI (Very Long Baseline Interferometry, [1]), and DORIS (Doppler Orbitography and Radio Positioning Integrated by Satellite, [5]). In 2014, we had compared troposphere zenith total delays (ZTD) and horizontal total gradients derived from IGS and IVS co-located sites [10]. During the last two years, with the collaboration of Dr. Vincenza Tornatore as the PMD (Politechnico di Milano) AC's team coordinator, we have compared site position time series extracted from combined solutions submitted by three official Combination Centers (CCs) belonging to IVS, IGS, and IDS that have contributed to the realization of the International Terrestrial Reference Frame 2014 (ITRF2014, [3, 11]). In particular the height component time series extracted from official combined intra-technique solutions submitted for ITRF2014 by VLBI, GNSS, and DORIS Combination Centers have been investigated to assess the level of agreement among these three space-geodetic techniques. The estimated velocities and their standard deviations for the sites that co-located the VLBI, GNSS, and DORIS stations were compared.

With the call [12] for participation for the computation of ITRF2014, ACs belonging to individual geodetic services of the IVS, IGS, and IDS reprocessed solutions according to common guidelines in the IERS Conventions 2010 [13]. In this work, harmonic analysis was carried out on the geodetic discrete irregular sampled time series residuals by using the software Frequency Analysis Mapping On Unusual Sampling (FAMOUS) developed by [14]. The IVS Up component time series analyzed in this work is derived from the combined solution calculated for ITRF2014. This combined solution is named as ivs2014a. 25 sites, at least five years of observations, and at least two sessions per month were chosen for analysis. For these sites, eight discontinuities in the Up direction were detected and removed. Two classes of signals related to seasonal (represented with dashed lines) and tidal effects (continuous lines) were detected (Figure 2).

During 2015 and 2016, we also analyzed several IVS Intensive sessions through reducing GNSS troposphere zenith total delays and horizontal total gradients from VLBI observations a priori to the parameter estimation with the collaboration of the Vienna AC working group at the Vienna University of Technology (TU Wien). We found slight improvement of the agreement of the length of day (LOD) with that from IGS [6] when east horizontal total gradients are reduced a priori from the observations of the IVS Intensive sessions [15].

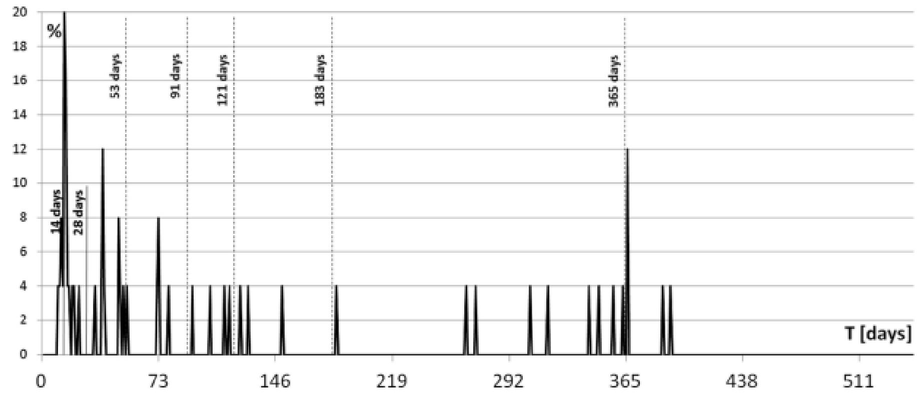

Fig. 2 Percentage of VLBI sites where a signal of period T is detected. (The periods of the expected tidal (−) and solar (−−) harmonics are evidenced).

4 Future Plans

In 2017 and 2018, our group will be working on the comparison of the VLBI parameter estimation results from data analysis performed by Kalman Filter (KF) and classical Least Squares Method (LSM), and we will continue to investigate UT1-UTC from IVS Intensive sessions.

Acknowledgements

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NICT VLBI Analysis Center Report for 2015–2016

Mamoru Sekido

Abstract The VLBI analysis activity of NICT is focusing on distant clock comparisons with small diameter broadband stations. Broadband VLBI observations between small and large diameter stations have become available. A series of domestic broadband VLBI sessions have been conducted in 2016. The broadband VLBI data showed advanced precision even with small diameter antennas. A signal processing path has become available from VLBI observation, correlation processing, bandwidth synthesis, registration to Mk3DB, up to VLBI analysis with CALC/SOLVE. We could show that the broadband delay observable has sufficient precision even with small diameter stations. Further improvement of VLBI analysis will depend on how much we could reduce atmospheric excess delay by observation strategy.

1 General Information

The Space-Time Standards Laboratory (STSL) of the National Institute of Information and Communications Technology (NICT) has been conducting broadband VLBI system development and observations with it. The VLBI group is located at the Kashima Space Technology Center. A research subject of the VLBI group of NICT is the application of the VLBI technique in precision frequency comparisons over intercontinental distances. The broadband VLBI system named GALA-V, which is compatible with VGOS specifications [1], has been developed for this application. The VLBI observation scheme for clock comparisons is basically the same as for standard geodetic VLBI sessions except that the session length is not limited to 24 hours, but it can last as long as 48–62 hours or more. Since our VLBI analyses have been performed mainly for technology development, this report focuses on the analysis for geodesy and time-and-frequency transfer with the broadband VLBI system.

NICT/ Kashima Space Technology Center

NICT Analysis Center

IVS 2015+2016 Biennial Report

2 Component Description

The VLBI application for frequency transfer is the current mission of our project, and the clock parameters estimated by VLBI sessions are the products as the clock difference between two VLBI stations. The observation strategy of a VLBI session for clock comparison is basically the same as for a standard VLBI session for geodesy. To get a better separation of the estimation parameters, observations are made of extragalactic radio sources in different directions in the sky by frequent switching. Broadband VLBI observations with GALA-V [2] acquire four channels of 1-GHz bandwidth data. Cross correlation processing of the broadband VLBI data is made by the GICO3 [3] software correlator, and the results are stored in Mark III databases through a data conversion with MK3TOOLS [4]. Then VLBI data analysis package CALC Ver.11.01 and SOLVE Ver.2014.02.21 developed by NASA/GSFC is used for the data analysis.

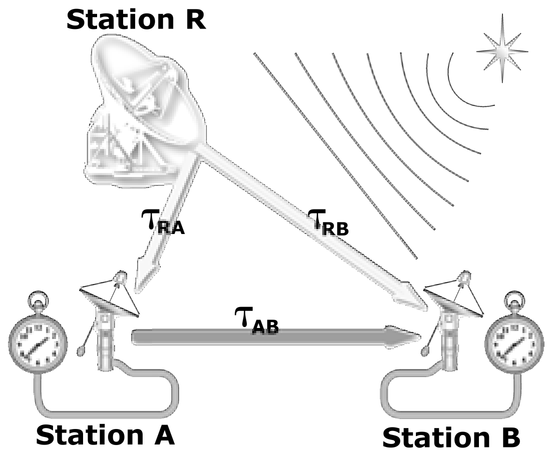

Fig. 1 The concept of the distant frequency comparison project GALA-V is composed of a pair of small-diameter antennas and one large-diameter antenna. Transportable small-diameter antennas are placed in laboratories, where the atomic frequency standards to be compared are located. The sensitivity of the VLBI observation between a pair of small-diameter antennas is boosted by joint observation with large-diameter antennas.

3 Staff

Members who are contributing to the Analysis Center at NICT are listed below (in alphabetical order):

- KONDO Tetsuro: Maintenance of correlation software K5VSSP and development of broadband bandwidth synthesis software.
- SEKIDO Mamoru: Coordinating VLBI observing and making data analysis with CALC/SOLVE.
- TAKEFUJI Kazuhiro: Data processing of broadband data and development of broadband VLBI observation system.

4 Activities during the Past Years

4.1 Frequency Transfer by Means of VLBI

Space-geodetic techniques such as GNSS have been proven to be useful tools for time and frequency transfer purposes. VLBI is another space-geodetic technique that can be utilized for frequency transfer. In contrast to GNSS, VLBI does not require any orbital information. It directly refers to an inertial reference frame defined by the location of the quasi-stellar objects. Being free from the availability of communication satellites and its transponder rental cost are further advantages of VLBI with respect to the two-way satellite time and frequency transfer (TWSTFT) technique.

The concept of our project (GALA-V) is displayed in Figure 1. Transportable small-diameter antennas are placed in laboratories, where atomic frequency standards to be compared are located. A sufficient signal to noise ratio (SNR) is gained by joint observations with small and large-diameter antennas. By using the closure relation of delay, the VLBI delays for the pair of small diameter antennas are derived, and the delay data are stored in Mark III databases and analyzed.

The delay observable (τ_{AB}) between the small diameter antenna pair (AB) is computed by linear combination of those (τ_{RA} and τ_{RB}) of the small and large diameter baselines (RA and RB) as follows:

$$\begin{aligned} &\tau_{AB}(t_{prt}) \\ &= \tau_{RB}(t_{prt} - \tau_{RA}(t_{prt})) - \tau_{RA}(t_{prt} - \tau_{RA}(t_{prt})) \\ &\cong \tau_{RB}(t_{prt}) - \tau_{RA}(t_{prt}) - \frac{d}{dt}\tau_{AB}(t_{prt}) \times \tau_{RA}(t_{prt}), \end{aligned} \quad (1)$$

where t_{prt} is the reference epoch of the observation. Radio source structure affecting the closure relation is subject to being investigated, and that is in the scope of our research.

One of the small-diameter antennas equipped with a broadband feed and high speed data acquisition system was installed at the National Meteorology Institute of Japan (NMIJ) in Tsukuba in 2014. Another small antenna is located at NICT Headquarters in Koganei, Tokyo. Both NMIJ and NICT are the national institutes engaged in the development of atomic frequency standards and are keeping the time series of UTC(NMIJ) and UTC(NICT), respectively.

By development of original broadband feeds, the IGUANA-H [6] and NINJA feeds, two small antennas and the Kashima 34-m antenna were upgraded to allow for broadband observations and have had their sensitivity improved step by step. Broadband bandwidth synthesis software has been developed [7] to derive precise delay observables from four bands of 1 GHz wide data.

In 2016, four bands of 1 GHz width of data acquisition became ready at our three stations, and the signal path from observation to data analysis has become available. A series of test VLBI sessions conducted in 2016 are listed in Table 1. Unlike with standard VLBI sessions, the session length is as long as 48–62 hours

Table 1 Broadband VLBI experiments conducted in 2016. The abbreviations of station names are as follows: Kas34: Kashima 34-m antenna, MBL1: MARBLE1 1.6-m diameter antenna at NMIJ, MBL2: MARBLE2 2.4-m diameter station at NICT Koganei.

Session Date	Stations	No.Scans (Used/Total)	Session Length
26-27 Jan.	Kas34-MBL1-MBL2	1330/1500	46 hours
12-13 Feb.	Kas34-MBL1-MBL2	1250/1600	47 hours
28-29 Feb.	Kas34-MBL1-MBL2	1050/1450	49 hours
16-17 May	Kas34-MBL1-MBL2	1220/1410	31 hours
24-25 Jun.	Kas34-MBL1-MBL2	1800/1850	49 hours
10-11 Jul.	Kas34-MBL1-MBL2	1960/2003	48 hours
23-24 Aug.	Ish13-MBL1-MBL2	1372/1385	43 hours
12-13 Sep.	Ish13-MBL1-MBL2	1600/1640	35 hours
25-28 Nov.	Kas34-MBL1-MBL2	2193/2237	62 hours
09-12 Dec.	Kas34-MBL1-MBL2	2022/2063	62 hours

because the project target is monitoring the clock difference.

The post-fit residuals and a histogram of the residuals of the VLBI session on 25–28 November are displayed in Figure 2. The residual plot in panel (a) was made by analysis of the A(NMIJ)-B(NICT) baseline, whose delay data were derived by equation (1) from delay data of the R(Kashima34)-A and the R-B baselines. The weighted RMS of the residuals was 14.2 ps in this case. Figure 2 (b) shows the histograms of residuals for the AB baseline and the RA and RB baselines. Because the delay observable of the AB baseline is computed by linear combination of the delay observable for RA and RB, the error of the delay observable is the root-sum-square of that of the RA and RB baselines by error propagation law. However, the histogram plot shows that the error residual distribution of the AB baseline data does not extend with respect to those of the RA and RB baselines. This suggests that the broadband delay observable is sufficiently precise, and the residual as an indicator of the analysis error is dominated by other causes, which is thought to be the uncertainty of the atmospheric delay.

We assume that the measurement data of the clock difference is the estimated clock parameter plus the residuals of VLBI analysis. The clock difference between UTC(NMIJ)-UTC(NICT) obtained by the VLBI session of 25–28 November is plotted in Figure 3 (a). The clock difference measured by GPS observations provided from BIPM is plotted also. The absolute difference between the clocks is difficult to measure for VLBI; then the offset of the vertical position of VLBI

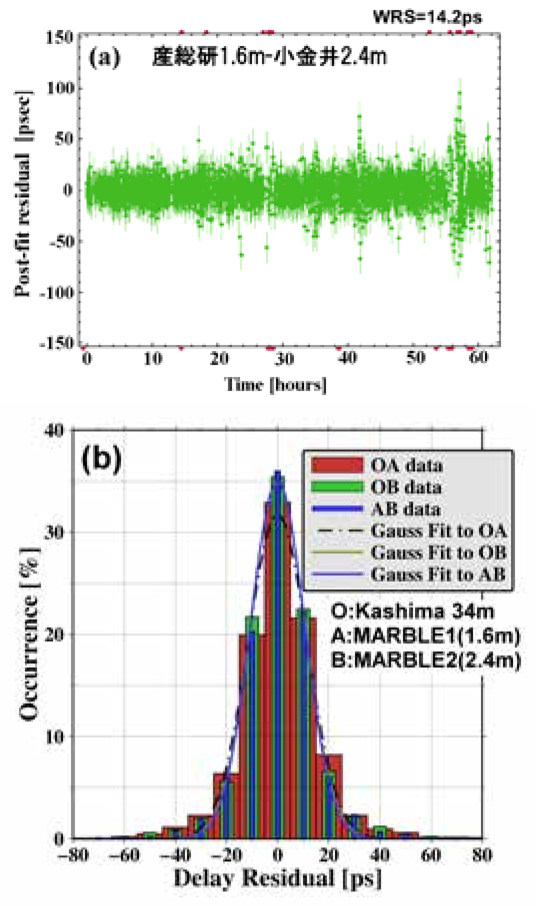

Fig. 2 (a) Post-fit residuals of the VLBI session on 25–28 November for the NICT–NMIJ baseline. (b) Histograms of the distribution of residuals are plotted for the AB and RA, RB baselines.

data in Figure 3 (a) is adjusted to be appropriate for comparison with GPS data. The Allan standard deviation computed from each of the time series and their differences are displayed in panel (b). Because the true clock difference is not known, we cannot say which technique has better performance from the data, although it is proven that VLBI observations between a pair of small diameter antennas works for clock comparisons with a performance no worse than that of GPS.

4.2 Other Activities

Space Geodesy Software Package C5++: The analysis software package for Space Geodesy (SLR,

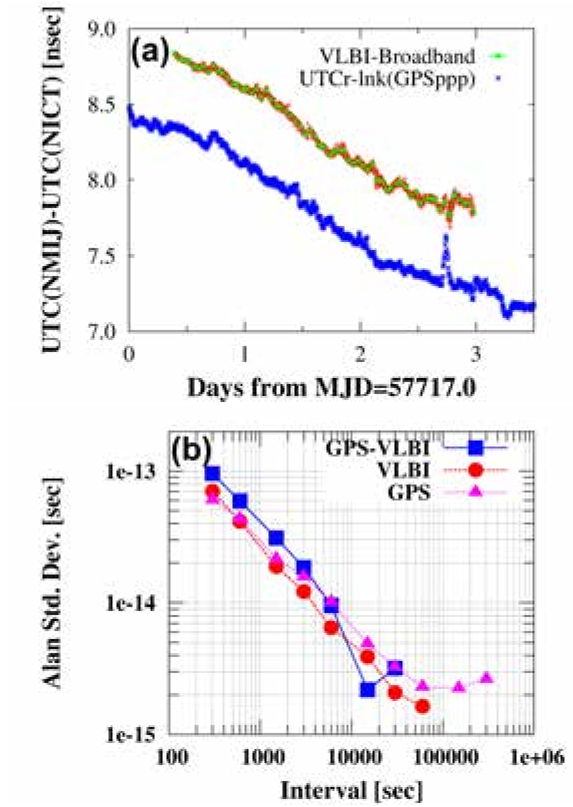

Fig. 3 The clock difference series between NICT and NMIJ compared by VLBI('×') and GPS('*') observations are plotted in panel (a). Allan standard deviation of each time series and their differences are plotted in panel (b).

VLBI, and GNSS) "C5++" [5], has been conducted under multi-organization collaborations. NICT is taking a part in the development and maintenance of the software.

MK3TOOLS: Software package MK3TOOLS, which is a platform-independent VLBI database format with NetCDF, was originally developed by T. Hobiger during his stay at NICT. Currently T. Hobiger at Chalmers Univ. of Tech. of Sweden and M. Sekido of NICT are jointly maintaining the package.

5 Future Plans

We are going to continue broadband VLBI sessions using domestic baselines. After we can confirm the performance and the stability of the system, we are willing to export one of the small VLBI stations to foreign institutes to test and evaluate the performance of GALA-V system for distant clock comparison.

Acknowledgements

We thank Dr. Kennichi Watabe, Dr. Tomonari Suzuyama, and Dr. Kazumoto Hosaka of NMIJ for their support of the frequency transfer experiment project at the NMIJ site. High speed data transfer between Kashima and Koganei is supported by the research network testbed JGN.

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Norwegian Mapping Authority Analysis Center Biennial Report 2015–2016

Ann-Silje Kirkvik

Abstract In 2015 Norwegian Mapping Authority (NMA) decided to discontinue the development of GEOSAT. Instead the development of a new software called Where started. Where will continue with some of the ideas from GEOSAT, but with a more modern software architecture and technology platform. The VLBI version of Where was almost complete by the end of 2016. NMA participated in VASCC2015 using GEOSAT and intends to participate with Where in the next phase of the campaign.

1 General Information

NMA has been an Associate Analysis Center within the IVS since 2010. The Analysis Center is operated by the Geodetic Institute at NMA with main offices in Hønefoss, Norway. NMA is a governmental agency and the IVS activities at NMA are completely funded by the Norwegian government.

NMA was using the analysis software GEOSAT. GEOSAT was originally developed by Per Helge Andersen (retired) at the Norwegian Defense Research Establishment (NDRE). The GEOSAT source code was finally abandoned in favor of creating a new software package with an improved architecture and using a more modern technology platform. The new software is called Where.

The new software should be able to process observations from VLBI, GNSS, SLR, and DORIS and will become an important tool at NMA for improving the global geodetic reference frame. Where is implemented in Python and utilizes several well-known packages such as `numpy`, `scipy`, and `matplotlib`. In addition, more specialized packages such as `astropy`[1] and `jplephem`[2] are also used. Where is a command line tool, but the the results can be inspected using the graphical tool called There that is being developed alongside Where.

Norwegian Mapping Authority (NMA)

NMA Analysis Center

IVS 2015+2016 Biennial Report

2 Staff

The Geodetic Institute at NMA has approximately 50 employees. Some of the responsibilities include maintaining the national reference frame, geoid, and height system. The Geodetic Institute also provides a network-RTK positioning service and operates the VLBI station at Ny-Ålesund. The Where project team consists of six members. These members are briefly described in Table 1.

3 Activities during the Past Year

In 2015, NMA decided to participate in the VLBI Analysis Software Comparison Campaign (VASCC2015) organized by Ph.D student Grzegorz Klopotek at Chalmers University of Technology, Sweden. The goal of the campaign was to compare computed theoretical delays from different analysis

[1] http://www.astropy.org

[2] https://pypi.python.org/pypi/jplephem

Table 1 Where project team members.

Name	Background	Tasks
Laila Løvhøiden	Oil industry and co-chairing the UN-GGIM working group	Project manager
Michael Dähnn	Dipl.-Ing. in geodesy from the Dresden University of Technology	GNSS implementation
Ingrid Fausk	Ph.D. in mathematics from the University of Oslo	SLR implementation
Geir Arne Hjelle	Ph.D. in mathematics from the Norwegian University of Science and Technology	Software architecture and assisting with all the techniques
Ann-Silje Kirkvik	M.Sc. in computer science from the Norwegian University of Science and Technology	VLBI implementation
Eirik Mysen	Ph.D. in astrophysics from the University of Oslo	Estimation techniques

software packages. NMA provided solutions using the GEOSAT software.

This work was very time consuming but turned out to be an extremely valuable experience. The need to modernize the software became exceedingly clear as GEOSAT was disassembled to be able to provide solutions for VASCC2015. GEOSAT provided consistent results compared with other software packages for geometrical, gravitational, and tropospheric delay and delay due to axis offset and thermal deformation. Figure 1 shows that the difference between c5++ and GEOSAT is less than 1 mm for all observations of that session. As mentioned in [2], the discrepancies between the software packages increased as high frequency EOP variations were included. The site displacement models still need to be compared.

Development of Where started in the second half of 2015. The experience from VASCC2015 was very helpful when implementing the VLBI model in Where, but no source code from GEOSAT has been used in Where. Where uses external libraries and functions such as SOFA[3] and the IERS Conventions 2010 software [4]. When the VLBI model was implemented in Where, the dataset from VASCC2015 was used to compare the theoretical delays with delays from GEOSAT. The results are shown in Figure 2, and they indicate that Where can calculate theoretical delays at the same level as the software packages that participated in VASCC2015. As with GEOSAT, the site displacement models and EOP variations still need more extensive testing.

[3] http://www.iausofa.org/2015_0209_F/sofa/sofa_pn.pdf

[4] http://maia.usno.navy.mil/conv2010/software.html

The Where project team visited Onsala Space Observatory in June 2016, where the group photo in Figure 3 was taken. The goal of this meeting was to share experiences and explore future possibilities for collaborations. The space geodesy field is very small in Norway, and being able to cooperate with similar groups in neighboring countries would be very beneficial. The meeting went well, and a new meeting is planned for February 2017 in Norway. This meeting also will include Toshimichi Otsubo, who is on a sabbatical at Onsala Space Observatory, which will provide an excellent opportunity to learn about the SLR implementation in c5++.

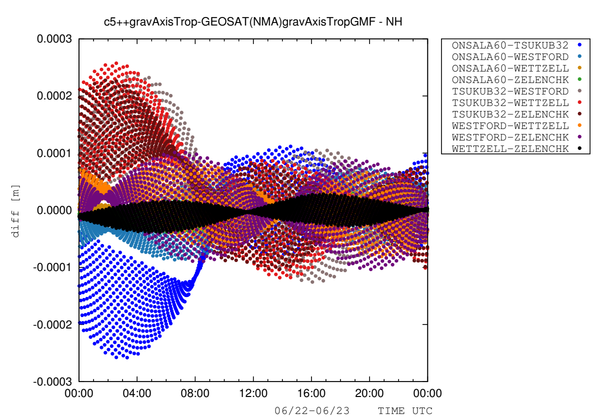

Fig. 1 Comparison of theoretical delays between c5++ and GEOSAT for the session 15JUN22CC_NH. This includes geometrical, gravitational, and tropospheric delay and delay due to axis offset. High frequency EOP variations and station displacement models are not included. Figure provided by Grzegorz Klopotek.

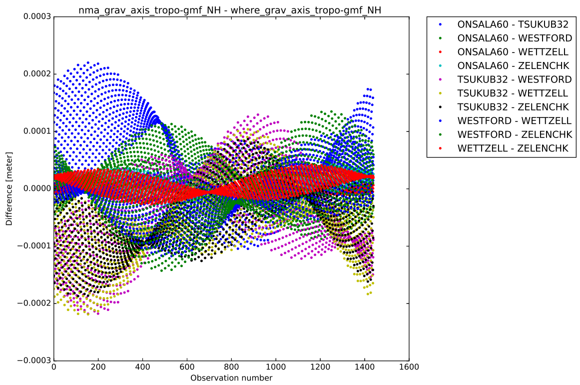

Fig. 2 Comparison of theoretical delays between GEOSAT and Where for the session 15JUN22CC_NH. This includes geometrical, gravitational, and tropospheric delay and delay due to axis offset. High frequency EOP variations and station displacement models are not included.

4 Current Status

The VLBI implementation in Where is almost ready for a beta release. The software can read NGS files and applies a VLBI model consistent with conventions ([5], [4]). Parameters are estimated using a Kalman filter (and smoother) where the nuisance parameters clocks and troposphere are modeled as continuous piecewise linear parameters. Using the results from [3], it is possible to create unconstrained normal equations in SINEX format based on the Kalman filter solution. This requires that all target parameters be estimated as a constant for the whole session.

The GNSS implementation is currently limited to GPS and the implementation of a Precise Point Positioning solution in Where, which is still under development. Development of the SLR implementation was halted due to maternity leave, but basic orbit determination was implemented. Development is expected to resume in the second half of 2017. Implementation of DORIS is completely on hold until the necessary resources become available.

5 Future Plans

The immediate main goal is to get a working version for VLBI analysis. The next step is to implement support for the new observation format vgosDb [1]. It has also been announced that the VLBI Analysis Software Comparison Campaign will continue in 2017, and NMA intends to participate using Where.

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Fig. 3 Visit at Onsala Space Observatory in June 2016. Back row from the left: Grzegorz Klopotek, Thomas Hobiger. Front row from the left: Joakim Strandberg, Niko Kareinen, Eirik Mysen, Geir Arne Hjelle, Laila Løvhøiden, Ingrid Fausk, Ann-Silje Kirkvik. Photo: Michael Dähnn.

Paris Observatory (OPAR) Analysis Center

Sébastien Lambert, César Gattano, Yann Ziegler, Ibnu Nurul-Huda, Christian Bizouard, Jean-Yves Richard, Christophe Barache, Teddy Carlucci

Abstract We report on operational and research activities directly related to VLBI at the Paris Observatory VLBI Analysis Center (OPAR) for calendar years 2015 and 2016. Our main achievements are (i) the emergence of a project on the Earth's interior by VLBI, (ii) the first direct estimate by VLBI of a deflexion parameter in the standard model extension (SME) framework, and (iii) the contribution to the validation process of the Gaia Data Release 1 catalog that used the competences of OPAR personnel in terms of assessments of reference frames.

1 Analysis Service

Paris Observatory Analysis Center OPAR continued operational analyses of VLBI diurnal and Intensive sessions. All the products, except SINEX files, were published on the OPAR Web site at

`http://ivsopar.obspm.fr`

together with exhaustive explanations and plots. SINEX files were only sent to the Data Centers.

SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, LNE

OPAR Analysis Center

IVS 2015+2016 Biennial Report

2 Research Activities

2.1 Nutation and Earth's Interior

In the last two years, we began working on the analysis of nutation time series with the aim of getting accurate estimates of Earth's interior parameters relevant to the core and the inner core. Years have elapsed since Mathews et al. (2002) obtained their excellent results. The accumulation of new data by various geodetic and geophysical techniques is particularly encouraging for undertaking a re-exploration of the Earth's interior by means of surface measurements. Especially, improving the accuracy of the resonant period of the free inner core nutation (FICN) is critical to constrain the dynamical ellipticity and density of the inner core, deformabilities of the core boundaries under fluid pressure, constants characterizing the viscomagnetic coupling at the core boundaries, viscosity of the inner core, friction at the inner-core boundary, and topographic torques at the interfaces.

In Rosat et al. (2017), we used nutation time series and surface gravity measurements by superconducting gravimeters together with a Bayesian inversion method to obtain the resonant period of the free core nutation (FCN) and the FICN. Though the FCN resonant period was found to be consistent between the two techniques and within the Mathews et al. error bars, the large confidence interval found for the FICN led to the conclusion that the FICN was possibly not detected at all or was vitiated by the presence of a poorly modeled atmospheric annual nutation. In another study, Gattano et al. (2017) analyzed the full set of VLBI nutation series available from the IVS Data Centers and revealed inconsistencies between series that were sufficiently large to destroy the robustness of the FICN estimate.

These two studies encouraged us to undertake a more ambitious project in at least two directions. A natural continuation of Rosat et al. (2017) is the combination of nutation and surface gravity data in a single matrix and a global inversion of common geophysical parameters (i.e., Chandler, FCN, and FICN resonances). This project started in October 2016 with the arrival of Yann Ziegler, geophysicist, at SYRTE, on a one-year postdoc position supported by the CNES. The second direction consists of estimating the above-cited geophysical parameters from a single inversion of the VLBI delays in a standard global VLBI solution. It will be realized by Ibnu Nurul-Huda, who began a PhD thesis at SYRTE in October 2016.

2.2 Testing Lorentz Symmetry by VLBI

Violations of Lorentz symmetry can be described as part of the field theory in the frame of the standard model extension (SME), containing both general relativity and the standard model used in particle physics. A hypothetical violation of Lorentz symmetry would alter the VLBI delay. This change can be parameterized and estimated directly by the analysis of VLBI delays. We introduced the partial derivative of the parameter constraining the amplitude of the violation in the pure gravity sector and got a direct estimation to the level of 10^{-5} (Le Poncin-Lafitte et al., 2016). This work has two main qualities: firstly, it improves by an order of magnitude the constraint on the above-cited parameter with respect to previous studies using Gravity Probe B and binary pulsar data, and, on the other hand, it is based on a direct estimate as opposed to postfit estimates that are performed on the residuals.

2.3 Multitechnique Combination

OPAR facilities were used for creating inputs with Calc/Solve to the French DYNAMO software package that allows the combination of normal equations from VLBI, GNSS, SLR, LLR, and DORIS and with which we obtained a 13-year long EOP series based on the combination of VLBI and GNSS (Richard et al., 2016). In the near future, DYNAMO will directly read IVS combination SINEX outputs as well as SINEX outputs from other technique centers of the IERS. The goal of this enterprise is to provide an operational solution obtained from a consistent combination of VLBI, GNSS, Laser ranging, and DORIS in parallel to the IERS EOP 14 C 04 data.

2.4 Validation of Gaia DR1 Catalog

Personnel of OPAR were involved in the validation phase of the first Gaia Data Release (Gaia DR1) in the framework of the Gaia Data Processing and Analysis Consortium (DPAC) coordination unit 9 (CU9) (Arenou et al., 2017). Our segment of the full validation process consisted essentially of characterizing the deformation between the Gaia DR1 catalog and the ICRF2, for which we provided and tested a six-parameter transformation consisting of three rotations and a glide.

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Onsala Space Observatory – IVS Analysis Center Activities during 2015–2016

Thomas Hobiger, Niko Kareinen, Grzegorz Klopotek, Rüdiger Haas, Joakim Strandberg, Hans-Georg Scherneck

Abstract This report gives a short summary on the ongoing and planned future activities of the IVS Analysis Center at the Onsala Space Observatory during 2015–2016.

1 General Information

In this report we describe our research activities related to space geodesy and geosciences at the Onsala Space Observatory. This includes geodetic VLBI and complementary techniques.

2 Activities during the Past Two Years

The main research topics during the time period were:

- Automated analysis of the IVS Intensive sessions and robust ambiguity estimation;
- Combining VLBI and GNSS for intercontinental frequency transfer;
- VLBI analysis software comparison campaign 2015;
- Extension of the c5++ analysis software;
- Ultra-rapid earth rotation determination with VLBI during CONT11 and CONT14;
- VLBI observations of near-field targets;
- Combining multiple signals for GNSS-reflectometry (GNSS-R);
- Ocean tide loading;
- Gravimetry observations.

Chalmers University of Technology, Department of Earth and Space Sciences, Onsala Space Observatory

Onsala Analysis Center

IVS 2015+2016 Biennial Report

3 Automated Analysis of the IVS Intensive Sessions

We explored different ways to improve the IVS Intensive sessions using the c5++ VLBI analysis software in a fully automated fashion. The Intensive sessions between 2001 and 2015 observed on the Kokee–Wettzell baseline were analyzed starting from Version-1 databases [3]. These databases consist of the raw delays from the correlator and thus contain outliers and ambiguities. The software c5++ was used to first resolve the ambiguities, after which the resulting databases were analyzed using different analysis setups. The following aspects were investigated:

- The impact of choosing GMF(GPT2) or VMF1 as the mapping function.
- The effect of applying the cable delay data.
- The dependence of the UT1–UTC accuracy on the a priori EOPs.
- The possibility of simultaneously estimating UT1–UTC and one of the station positions.

Based on the results, we conclude that for UT1–UTC accuracy the most significant factor is the availability of recent (1–2 days) a priori polar motion (see Figure 1). Furthermore, improving the accuracy of UT1–UTC estimated from the Intensive sessions would require implementing fundamental changes in the current Intensive session strategy.

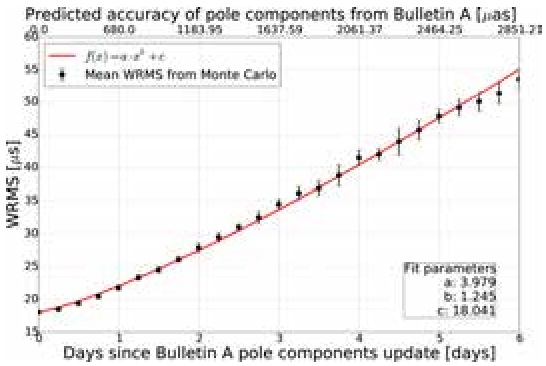

Fig. 1 Mean WRMS of UT1-UTC residuals w.r.t. C04. The X-axis shows days elapsed since the Bulletin A epoch (bottom) and corresponding polar motion accuracy (top).

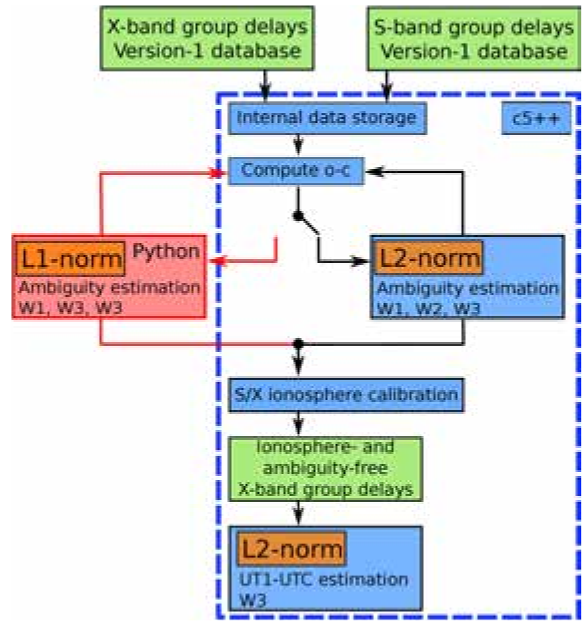

Fig. 2 The schematics of the implemented ambiguity estimation methods in c5++.

The standard scheme in c5++ uses least-squares analysis to automatically estimate the group delay ambiguities resulting from bandwidth synthesis. As an alternative to this strategy, we implemented a robust ambiguity estimation method using the L1-norm instead of least-squares adjustment (see Figure 2) [4]). Again, the set of VLBI sessions was the Version-1 databases between 2001 and 2015. The robust estimation method increased the success rate of the ambiguity estimation by approximately 5%.

4 Combining VLBI and GNSS for Intercontinental Frequency Transfer

For decades, GPS has been the only space geodetic technique routinely used for inter-continental frequency transfer applications. In the past VLBI has also been considered for this purpose and the method's capabilities were studied several times. However, compared to GPS, current VLBI technology only provides few observations per hour, thus limiting its potential to improve frequency comparisons. We therefore investigated the effect of combining GPS and VLBI on the observation level in order to draw the maximum benefit from the strength of each individual technique. GPS and VLBI single-technique analysis revealed similar frequency link instabilities at the level of 10^{-14} to 10^{-15} (modified Allan deviation) on inter-continental baselines for averaging times of one day (cf. Figure3). A combined analysis of both techniques led to small but consistent improvements for frequency transfer of up to 10, in particular for averaging periods longer than 3,000 s [2].

5 VLBI Analysis Software Comparison Campaign 2015

The aim of the VLBI Analysis Software Comparison Campaign 2015 (VASCC2015) was to compare different VLBI analysis software packages on the basis of computed theoretical delays. This included packages which are used for operational VLBI analysis as well as those which are still under development. During VASCC2015 numerical issues were identified and several bugs could be fixed in some of the analysis packages. The results indicate that a sub-mm agreement of theoretical delays, computed by state-of-the-art VLBI analysis software packages, can be achieved [11].

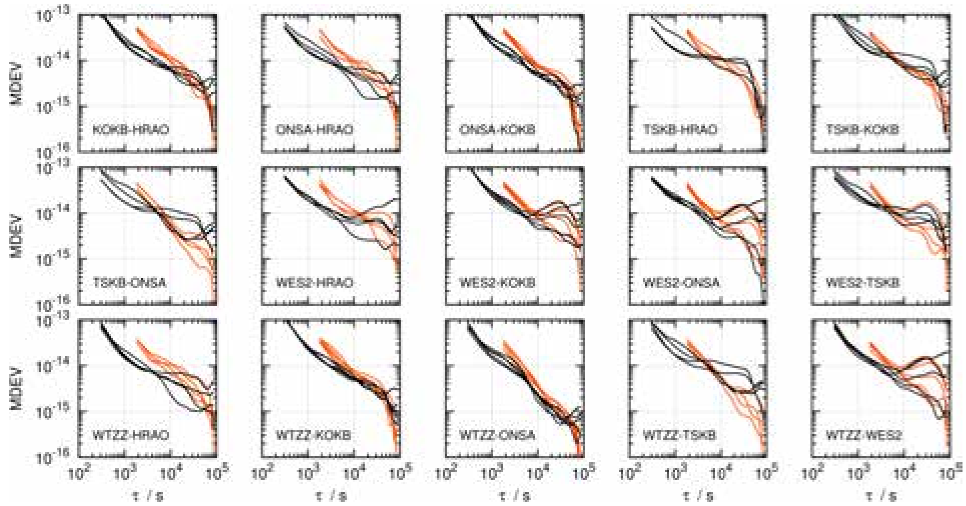

Fig. 3 Modified Allan deviation (MDEV) plots for frequency links over all baselines in a six-station CONT11 network, as obtained from the three-daily GPS (black) and VLBI (orange) single-technique solutions with c5++.

6 Extension of the c5++ Analysis Software

The VLBI part of the c5++ software was extended with an interface capable of reading VLBI observations stored in the vgosDB format. Further changes relate to the implementation of two near-field VLBI delay models described by [9] and [10]. The latter allowed us to correlate test observations to the Chang'E-3 lander that were carried out in April 2014 on the ONSALA–WETTZELL baseline. This was achieved by including c5++ into the processing chain as depicted in Figure 4.

7 Ultra-rapid Earth Rotation Determination with VLBI during CONT11 and CONT14

We compared the earth rotation results derived from the ultra-rapid operations on the Onsala–Tsukuba baseline during the continuous VLBI campaigns CONT11 and CONT14 to results from post-processing of the complete CONT network sessions, as well as Intensive sessions during CONT11 and CONT14 [1]. As a common reference for the comparison we used the IERS 08 C04 series. Our results show that the accuracies of the CONT ultra-rapid single baseline operations are roughly a factor three times worse than the results from both dedicated one-baseline sessions and/or the complete analysis of network sessions. The reason is that the ultra-rapid sessions during the CONTs were not optimized for earth rotation determination.

8 VLBI Observations of Near-Field Targets

Together with IVS partner telescopes, we performed experimental observations of near-field targets. The latter included the Chinese Chang'E-3 Lunar lander (S/X-band), the Chinese APOD satellite (X-band), and GNSS-satellites (L-band). We used the extended c5++ software (see Section 6) to prepare the necessary a priori files for the data correlation with the software correlator DiFX, and we were able to successfully correlate the observed data.

9 GNSS-R Measurements of the Coastal Sea Level

We investigated new ways of retrieving sea surface height from GNSS-reflectometry (GNSS-R) in which signals from different constellations and frequencies are used in a combined solution. By inverse modeling of the signal-to-noise ratio (SNR), the height can be modeled as a continuous function shared across the different signals available at a single epoch. The results

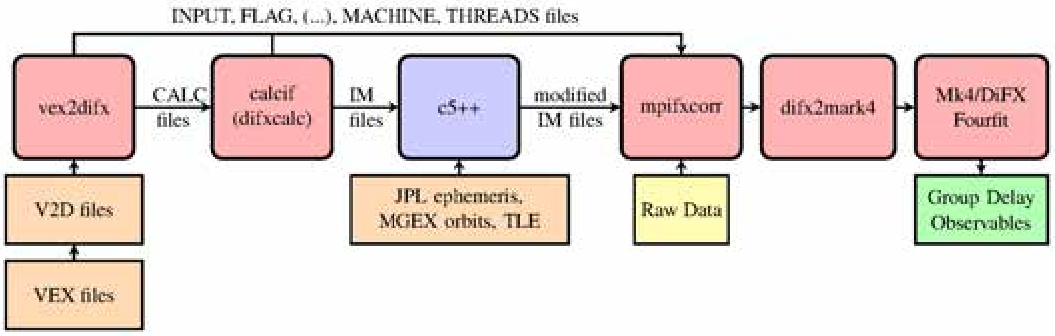

Fig. 4 Simplified schematics of the VLBI data correlation in DiFX and multi-band synthesis using common processing chain supplemented by the c5++ analysis software.

demonstrate that this approach is more precise than the previously used spectral analysis [5]. Even using only a single signal, the method shows an increased precision, and using multiple signals in the processing increases the precision even further. With root mean square differences of about 15 mm w.r.t. an official tide gauge, the method has been proven to lead to an improvement of more than 50% as compared to previous single receiver solutions computed for the same period.

10 Ocean Tide Loading

In 2016, new ocean tide models were added to the catalog of the Free Ocean Tide Loading provider (`http://holt.oso.chalmers.se/loading`), FES2014a [6] and TPXO8-Atlas [7]. Actually, the requests for loading coefficients are forwarded to the computing site at SEGAL located at the University of Beira Interior and Institute Dom Luiz, UBI/IDL in Portugal. Machiel S. Bos has kindly made this computational load relieving facility available. During 2015 and 2016, 12,622 requests were served for 189,515 observing sites.

11 Gravimetry Observations

The Superconducting Gravimeter (SG, model GWR #54, station code OS) has been observing continuously during the period of this report; only one of the 1.5 billion one-second samples has been lost. Efforts are on-going to provide an empirical SG-based station model for reduction of regular and anomalous gravity variations, parameters that we contribute to visiting Absolute Gravity (AG) groups. Four AG campaigns were carried out in the two years, including a visit with a novel quantum interferometer design developed at Humboldt University Berlin, Germany [8]. Observation data are reported to the IGETS (formerly GGP) database at GfZ Potsdam, Germany. A live page rich with links is available at `http://holt.oso.chalmers.se/hgs/SCG/`.

Modeling work for the gravimetry station at OSO makes use of the broadband seismometer station located there and run by Uppsala University within their Swedish National Seismograph Network.

12 Future Plans

The main focus of our work for the coming years will be the Onsala Twin Telescopes project. We look forward to the official inauguration of the telescopes in the spring of 2017. Upon completing the signal chain the project can proceed to the testing phase and later to operational use. We anticipate many interesting experiments and corresponding data analysis that will help to fine-tune the OTT systems. We also will work on tying the new telescopes into the observatory network. In 2017 we also expect to install a new microwave radiometer close to the OTT, which, together with the other sensors, will allow to intensify studies concerning atmospheric turbulence and its impact on space geodetic measurements. The work done with the IVS Intensives to find new and automated ways to analyze VLBI data will be continued, aiming to find improved observing and analysis strategies for VGOS era observations. We will continue with observations of near-field targets and focus on the corresponding data analysis. Furthermore, there is an ongoing effort to greatly improve the GNSS-R observations of the sea level and to further expand the concept.

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Biennial Report (2015–2016) of PMD IVS Analysis Center

Vincenza Tornatore

Abstract The main activities carried out at PMD IVS Analysis Center during 2015 and 2016 are summarized in this report and plans for 2017 are briefly pointed out. Three main subjects were tackled during 2015 and 2016. One concerns the so-called space ties; in this framework a number of GNSS observation tests have been proposed, planned, and carried out with European VLBI antennas. A second investigation was dedicated to VLBI coordinate time series analysis and comparison with corresponding results from other space geodetic techniques involved in ITRF2014 computation. Finally, data processing of CONT campaigns have been carried out for studies on tropospheric parameter estimation from VLBI data and comparison with GNSS estimates at co-location sites.

1 General Information and Staff

The Department of Civil and Environmental Engineering (DICA) of the Polytechnic University of Milan hosts the Politecnico di Milano DICA (PMD) IVS Analysis Center (AC). Milan Polytechnic is the largest technical university in Italy with about 40,000 students. It offers undergraduate, graduate, and higher education courses in engineering, architecture, and design. The Milan Polytechnic has seven main campuses, two are in Milan city and five across Lombardy and Emilia Romagna. The majority of the research and teaching activities are located in the historical campus called Milano Leonardo. PMD AC is located at this campus, in particular it is supported by the Geodesy and Geomatics research area of DICA as far as hardware equipment, software licenses, and assistance are concerned. Members who cooperated with the activities of the PMD IVS Analysis Center in 2015 and 2016 are listed in Table 1.

Politecnico di Milano, Department of Civil and Environmental Engineering (DICA), Geodesy and Geomatic Area

PMD Analysis Center

IVS 2015+2016 Biennial Report

Table 1 PMD IVS AC support staff in 2015 and 2016.

Name	Working Location	Contribution to PMD
Vincenza Tornatore	Politecnico di Milano, DICA, Geod.Geom.Area, Milano, ITALY.	Responsible person from AC, project coordinator
Giovanna Venuti	Politecnico di Milano, DICA, Geod.Geom.Area, Como, ITALY.	Troposphere
Cinzia Vajani	Politecnico di Milano, DICA, Geod.Geom.Area, Milano, ITALY.	Software maintenance
Lorenzo Rossi	Politecnico di Milano, DICA, Geod.Geom.Area, Como, ITALY.	Support for data processing

Staff member contributions and working locations (see [1] and [2]) are indicated in the table as well.

2 Current Status and Activities

The main topics investigated during 2015 and 2016 continued to be related to the improvement of reference frames stability, to satellite/space geodetic inter-technique comparisons, and to troposphere parameter esimation from VLBI and GNSS observations at co-location sites. The scientific software used for data processing and analysis was updated to the last version available, and some home made algorithms were improved.

2.1 Planning and Realization of VLBI Observations of GNSS Satellites

The activities related to the planning and realization of GNSS satellite observations by the VLBI technique (that started some years ago, see, e.g., [17] and [18]), were carried out during the biennium 2015–2016. In particular in this period the experiments were devoted primarly to test the use of the DBBC3 [20] for the acquisistion of the strong satellite signal at Medicina VLBI station [3] and at the Sardinia Radio telescope (SRT) [4].

SRT is a large (64-m primary mirror with a 7.9 m secondary) radio telescope, fully steerable located in the province of Cagliari in Sardinia, inaugurated in 2013 (see Figure 1).

Fig. 1 A view of Sardinia Radio Telescope; credits by http://www.media.inaf.it/.

The use of the DBBC3 during VLBI observations of GNSS satellites has the advantage to automatically set the power attenuation on the very strong signal coming from the satellites. Then it also takes off the attenuation once the radio telescope receives the weak signal from celestial natural radio sources usually tracked during geodetic VLBI experiments.

One experiment was carried out on the 23 November 2015 on the single baseline between the VLBI stations Medicina and Wettzell. Three satellites for each constellation (GPS, GLONASS, GALILEO) were tracked, alternating satellite observations with natural radio source observations. The software used for scheduling GNSS and natural radio source observations was the VieVS satellite scheduling program [13], which is included as a module in the VieVS software [10]. First attempts of data correlation were successful, but the whole pipeline of the experiment data processing still needs to be completed.

A second experiment was carried out on the 23 May 2016; participating VLBI stations were Medicina, SRT, and Onsala85 [5]. This test was planned as a multi-station, multi-frequency, and multi-constellation experiment. In this case we observed not only GPS, GLONASS, and GALILEO, but also the Chinese Beidou constellation, as it is shown on the skyplot of Medicina station in Figure 2. Some, still unresolved, problems were found during the correlation of the data from the Medicina VLBI station. Investigating the reasons and possible solutions of the problems are in progress.

2.2 Satellite/Space Geodetic Inter-technique Comparisons

We carried our investigations on time series of site coordinates belonging to the networks of the three microwave space-geodetic techniques: Global Navigation Satellite Systems (GNSS) [12], Very Long Baseline Interferometry (VLBI) [16], and Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS) [21].

Figure 3 shows the networks of sites belonging to all four satellite/space-geodetic techniques contributing to ITRF2014, Satellite Laser Ranging (SLR) [8] included, as of mid-2014. In preparation of the computation of the new realization of the International Terrestrial Reference Frame ITRF2014 [9] all ACs, belonging to individual satellite/space-geodetic services of the International Association of Geodesy (IAG)—the International DORIS Service (IDS), the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS), and the International GNSS Service (IGS)—reprocessed data ac-

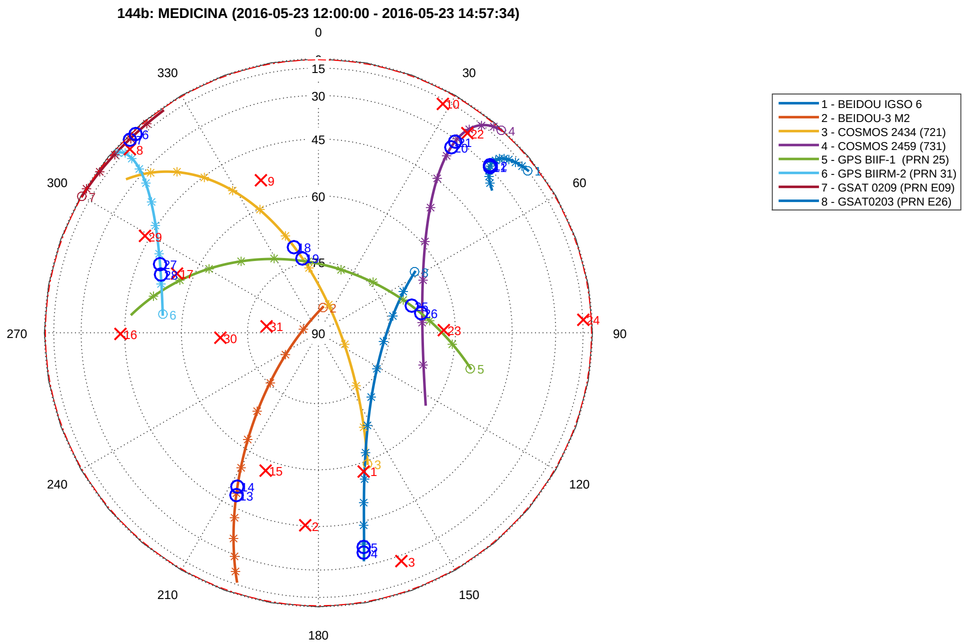

Fig. 2 Skyplot for one of the participating stations (Medicina) of the 23 May 2016 experiment; courtesy of A. Hellerschmied.

Fig. 3 The networks supporting the ILRS, IGS, IVS, and IDS; from [14].

cording to common guidelines and improved models conforming with the IERS Conventions 2010 [15] and updates posted at [6].

We based our studies on the site positions extracted from combined reprocessed input time series submitted for ITRF2014 computation by IVS, IDS, and IGS official Combination Centers (CCs). We used a novel approach to study time series that is described in detail in [19]. The analysis consists of three main steps: detection and removal of documented and undocumented discontinuities, modeling of the long-term signal (constraining the system dynamic in order to obtain cyclostationary residuals), residuals harmonic analysis by a non-linear least squares algorithm. Frequencies and amplitudes of the residual signals and their percentage of incidence were estimated. Two classes of residual signals related to seasonal and tidal effects were detected for all the three techniques. At the co-location sites (running regularly VLBI, GNSS, and DORIS observations) we estimated also velocities and their standard deviations (STD) obtaining a good agreement among the three techniques both in the horizontal (1.0 mm/yr mean STD) and in the vertical (0.7 mm/yr mean STD) component. Some sites show larger STDs, mainly due to lack of data, different data spans, or noisy observations.

This work was carried out in collaboration with KTU-GEOD Analysis Center (Karadeniz Technical University) and Department of Architecture and Design (DAD) of Polytechnic University of Turin.

2.3 Estimation of Atmospheric Parameters using VLBI and GNSS Data

During 2015 and 2016 the scientific software for VLBI and GNSS data processing was updated to the last version delivered by the universities developing and maintaining the software: the Department of Geodesy and Geoinformation of Vienna University of Technology and the Astronomical Institute of the University of Bern, respectively. The releases now running are the 2.3 for VieVS [7] and the 5.2 for Bernese software [11]. After a period of testing of the new software versions, CONT campaigns were processed using VieVS 2.3. At the VLBI stations co-located with GNSS permanent stations, we are going to process GNSS data too to estimate troposphere parameters using the Bernese 5.2. This work was developed in cooperation with the IVS AC-VIE at Vienna University of Technology (TU Wien). Analysis and comparisons of the results need to be completed.

Some tests, in collaboration with the IVS KTU AC, were carried out to analyze GNSS time series of ZTD (Zenith Tropospheric Delay) and IWV (Integrated Water Vapour) estimates.

3 Future Plans

The plans of PMD IVS Analysis Center for the 2017 and 2018 biennium concern the continuation of studies and experiments on the problem of co-location in space and on ground of the space-geodetic techniques VLBI and GNSS.

The studies and comparisons of the results from the three microwave space/satellite geodetic techniques (VLBI, GNSS, and DORIS) will be extended also to the SLR technique.

Studies on troposphere parameter estimation from VLBI and GNSS will also be continued and some investigations on ionosphere parameters are planned too.

Acknowledgements

We are grateful to the Department of Civil and Environmental Engineering (DICA) of Polytechnic University of Milan, in particular to the Geodesy and Geomatics Area for hosting and supporting the IVS PMD AC. Thanks are due to all the people contributing to activities of the IAG Services: IVS, IGS, IDS, and ILRS.

We thank KTU-GEOD IVS AC (Karadeniz Technical University) and IVS AC-VIE at Vienna University of Technology for their collaboration with some of the IVS PMD AC activities. In particular we thank A. Hellerschmied for having prepared the schedules of the tests mentioned in sub-section 2.1 and the staff at Medicina, SRT, Wettzell, and Onsala who contributed to the realization of the observations.

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Pulkovo Observatory IVS Analysis Center (PUL) Report 2015–2016

Zinovy Malkin, Yulia Lopez

Abstract This report briefly presents the PUL IVS Analysis Center activities during 2015–2016 and plans for the coming year. The main topics of the scientific investigations of the PUL staff in that period were ICRF related studies, EOP series analysis, celestial pole offset (CPO), and free core nutation (FCN) modeling. Regular activities include UT1 Intensive data processing, OCARS catalog support, and support of the PUL archives of data and products.

1 General Information

The PUL IVS Analysis Center was organized in September 2006. It is located at and sponsored by the Pulkovo Observatory of the Russian Academy of Sciences. It is a part of the Pulkovo EOP and Reference Systems Analysis Center (PERSAC) [1]. The main topics of our IVS related activities are:

- Improvement of the International Celestial Reference Frame (ICRF).
- Computation and analysis of the Earth orientation parameters (EOP) from Intensives and 24-hour IVS sessions.
- Analysis of EOP and source position time series.
- Modeling of the celestial pole offset (CPO) and free core nutation (FCN).
- Comparison of VLBI products, primarily EOP, with results of other space geodesy techniques.
- Computation and analysis of observation statistics.

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Pulkovo Analysis Center (PUL)

IVS 2015+2016 Biennial Report

The PUL Analysis Center Web page [2] is supported. Its contents was described in previous reports.

2 Staff

The following persons contributed to the PUL activities in 2015–2016:

1. Zinovy Malkin (70%) — team coordinator, EOP and CRF analyst;
2. Yulia Lopez (née Sokolova) (50%) — CRF analyst.

3 Activities and Results

The main activities and results of the PUL IVS Analysis Center during 2015–2016 included the following topics.

- *ICRF related research.*
  - We compared results of determination of the orientation angles between celestial reference frames realized by radio source position catalogs using three methods of accounting for correlation information: using the position errors only, using additionally the correlations between the right ascension and declination (RA/DE correlations) reported in radio source position catalogs published in the IERS format, and using the full covariance matrix [10]. The computations were performed with nine catalogs computed at eight Analysis Centers. Our analysis has shown that using the RA/DE

correlations only slightly influences the computed rotational angles, whereas using the full correlation matrices lead to substantial change in the orientation parameters between the compared catalogs.

– The current state of the link problem between radio and optical celestial reference frames was analyzed [11]. The main objectives of the investigations in this direction during the next few years are the preparation of a comparison and the mutual orientation and rotation between the optical *Gaia* Celestial Reference Frame (GCRF) and the 3rd generation radio International Celestial Reference Frame (ICRF3), obtained from VLBI observations. Both systems, ideally, should be a realization of the ICRS (International Celestial Reference System) at micro-arcsecond level accuracy. Therefore, the link accuracy between the ICRF and GCRF should be obtained with similar error level, which is not a trivial task due to relatively large systematic and random errors in source positions at different frequency bands. In this paper, a brief overview of recent work on the GCRF–ICRF link is presented. Additional possibilities to improve the GCRF–ICRF link accuracy are discussed. The suggestion is made to use astrometric radio sources with optical magnitude to 20^m rather than to 18^m as currently planned for the GCRF–ICRF link.
– Using radio stars for linking the optical *Gaia* Celestial Reference Frame (GCRF) to the VLBI-based ICRF was considered [9]. In this work, an obtainable accuracy of the orientation angles between GCRF and ICRF frames was estimated by Monte Carlo simulation. If the uncertainties in the radio star positions obtained by VLBI are in the range of 0.1–4 mas and those obtained by *Gaia* are in the range of 0.005–0.4 mas, the orientation angle uncertainties are 0.018–0.72 mas if 46 radio stars are used, 0.013–0.51 mas if 92 radio stars are used, and 0.010–0.41 mas if 138 radio stars are used. The general conclusion from this study is that a properly organized VLBI program for radio star observation with a reasonable load on the VLBI network can allow for the realization of GCRF–ICRF link with an error of about 0.1 mas.
– In collaboration with Geoscience Australia (Oleg Titov) a new approach was developed to facilitate the structure delay for extended radio sources using post-fit residuals calculated after processing of geodetic VLBI observations in the standard way. No imaging of a radio source is required for the new approach. In this method, the simplest model of a radio source including two point-like components can be represented by four parameters, namely angular separation, orientation, flux ratio, and difference of spectral indices [5] for each baseline of the multi-baseline VLBI network separately. To demonstrate the effectiveness of this approach, we have analyzed post-fit residuals of the radio source 0014+813 intensively observed during the two-week CONT14 campaign under the auspice of the IVS in May 2014. Large systematic differences in post-fit residuals for northern hemisphere baselines of 5,000 km and longer were detected. We have estimated all four parameters for each baseline and determined average characteristics of the 0014+813 radio structure at the frequency 8.4 GHz. The radio source is found to consist of two components separated by 0.5 mas and in north-south direction. Implementation of this structure model to analysis of the CONT14 data results in 0014+813 declination displacement of 0.070 mas in the north direction with respect to the reference position [14].
– The OCARS catalog (Optical Characteristics of Astrometric Radio Sources) [3] is supported. The catalog provides morphological type, redshift info, visual and NIR magnitudes, and cross-identification with other catalogs [12]. The latest OCARS version includes photometric data in 14 bands *uUBgVrRiIzJHKG*. Cross-identification table is yet only provided for IVS and LQAC catalogs.

- *CPO and FCN related research.*
  – Two CPO and two FCN series are being updated daily and are available at the PERSAC Web page [1].
  – A previous study (Malkin, 2013) revealed that the epochs of the observed extremes in the FCN amplitude and phase variations are close to the GMJ epochs. Recently, new evidence of this

connection was found [7]. The large FCN amplitude and phase disturbance occurred at the epoch close to the newly revealed GMJ 2011. This event occurred to be the second largest change in the FCN amplitude and phase after the 1999 disturbance that is also associated with the GMJ 1999. Moreover, the long-time FCN phase drift had changed suddenly in 1998–1999, immediately before the GMJ 1999, and seemed to change again at the epoch immediately preceding the GMJ 2011. The FCN amplitude showed a general long-time decrease before GMJ 1999, and it subsequently grew until GMJ 2011, and then seemed to decrease again. A smaller FCN change can be observed at the epoch around 2013, which is also suspected as the GMJ epoch. The latter confirms the suggestion that a rapid change in the FCN amplitude and/or phase can be used as evidence of the GMJ that is not clearly detected from the geomagnetic observations.

– Three combined celestial pole offset (CPO) series computed at the Paris Observatory (C04), the United States Naval Observatory (USNO), and the International VLBI Service for Geodesy and Astrometry (IVS), as well as six free core nutation (FCN) models, were compared from different perspectives, such as stochastic and systematic differences and FCN amplitude and phase variations [13]. The differences between the C04 and IVS CPO series were mostly stochastic, whereas a low-frequency bias at the level of several tens of μas was found between the C04 and USNO CPO series. The stochastic differences between the C04 and USNO series became considerably smaller when computed at the IVS epochs, which can indicate possible problems with the interpolation of the IVS data at the midnight epochs during the computation of the C04 and USNO series. The comparison of the FCN series showed that the series computed with similar window widths of 1.1 yr to 1.2 yr were close to one another at a level of 10 μas to 20 μas, whereas the differences between these series and the series computed with a larger window width of 4 yr and 7 yr reached 100 μas. The dependence of the FCN model on the underlying CPO series was investigated. The RMS differences between the FCN models derived from the C04, USNO, and IVS CPO series were at a level of approximately 15 μas, which was considerably smaller than the differences among the CPO series. The analysis of the differences between the IVS, C04, and USNO CPO series suggested that the IVS series would be preferable for both precession-nutation and FCN-related studies.

- Non-linear VLBI station motions and their impact on the celestial reference frame and Earth orientation parameters were investigated [6]. The increasing accuracy and growing time span of Very Long Baseline Interferometry (VLBI) observations allow the determination of seasonal signals in station positions which still remain unmodeled in conventional analysis approaches. In this study we focused on the impact of the neglected seasonal signals in the station displacement on the celestial reference frame and Earth orientation parameters. We estimated empirical harmonic models for selected stations within a global solution of all suitable VLBI sessions and created mean annual models by stacking yearly time series of station positions which were then entered a priori in the analysis of VLBI observations. Our results revealed that there is no systematic propagation of the seasonal signal into the orientation of celestial reference frame but position changes occurred for radio sources observed non-evenly over the year. On the other hand, the omitted seasonal harmonic signal in horizontal station coordinates propagates directly into the Earth rotation parameters causing differences of several tens of microarcseconds
- Operational data processing of IVS Intensive sessions in operational automated mode and submission of results to IVS was continued. The latest UT1 time series includes ~5,700 UT1 estimates for 1999–2016 and is available at the IVS Data Centers and at the PERSAC Web page [1].
- The PUL archive of VLBI data and products obtained in the framework of IVS activity is supported. At present, all available X-band NGS cards for ~15.5 thousand sessions observed in 1979-2016 are stored. The PUL NGS archive contains ~14 million (~12 good) observations and looks to be the most complete among other IVS NGS card archives.

- Development of algorithms and software for data processing and analysis continued. In particular, a review was prepared of the experience of using AVAR and its modifications in processing astronomical and geodetic time series [8].
- PUL staff members participated in activities of several IAG, IAU, IERS, and IVS projects, committees, and working groups.

4 Future Plans

Plans for the coming year include:

- Continuing ICRF related studies.
- Continuing CPO/FCN related studies.
- Continuing UT1 Intensive data processing.
- Continuing OCARS catalog support.
- Continuing development of algorithms and software for data processing.
- Continuing support of the PUL archives of data and products.

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SAI–VNIIFTRI VLBI Analysis Center 2015–2016 Report

Vladimir Zharov [1], Sergey Pasynok [2], Andrey Sinev [2]

Abstract This report presents an overview of the SAI–VNIIFTRI VLBI Analysis Center activities during 2015–2016 and the plans for 2017. The AC analyzes all IVS sessions for computations of the Earth orientation parameters (EOP), time series of the ICRF source positions, and performs research and software development aimed at improving the VLBI technique.

1 General Information

The SAI–VNIIFTRI VLBI Analysis Center is located at Sternberg State Astronomical Institute (SAI) of Lomonosov Moscow State University in Moscow and at the National Research Institute of Physicotechnical and Radio Engineering Measurements (VNIIFTRI), Mendeleevo, Russia. The Analysis Center participates in geodetic and astrometric VLBI analysis, software development, and research aimed at improving the VLBI technique, and especially for support of the ASC correlator during the Radioastron mission [1].

2 Activities during the Past Two Years

The SAI–VNIIFTRI AC performs data processing of all kinds of VLBI observation sessions. For VLBI data analysis we use the ARIADNA software package developed by V. Zharov [2]. Version 4 of this software was finished and tested in 2015. All reductions are performed in agreement with the IERS Conventions (2010). The software package uses files in NGS format as input data.

ARIADNA (v. 4) is the base of the ORBITA software installed on the correlator of the AstroSpace Center at the Lebedev Physical Institute. It is used for correlation of the ground–space interferometer data during the Radmoastron mission.

Staff of the joint AC are:

- Vladimir Zharov, Prof.: development of the ARIADNA software, development of the methods of parameter estimation (SAI);
- Sergey Pasynok, scientific researcher: global solution (VNIIFTRI);
- Andrey Sinev, engineer: VLBI data processing (VNIIFTRI); and
- Natalya Shmeleva, engineer: VLBI data processing (SAI).

3 Current Status

- **Software development for VLBI processing**
  The ARIADNA software is being developed to provide contributions to IVS products. The software is used for calculating all types of IVS products. The main features of version 4 are: all reductions are performed in agreement with the IERS Conventions (2010), the automatic generation of the SINEX files, and the combination of some of the SINEX files to stabilize the solution.

1. Sternberg State Astronomical Institute (SAI) of Lomonosov Moscow State University
2. National Research Institute of Physicotechnical and Radio Engineering Measurements (VNIIFTRI)

SAI–VNIIFTRI Analysis Center

IVS 2015+2016 Biennial Report

The used version of software was corrected in 2015; now it is possible to use the CIO-based transformation matrix. A new set of EOP series was obtained from observations that were made in 2015–2016.

The method that uses calculation of the equinox-based transformation matrix for precession-nutation was kept to compare the new series with the old ones. The equinox-based matrix $Q(t)$ that transforms from the true equinox and equator of date system to the GCRS composed of the classical nutation matrix, the precession matrix including four rotations, and a separate rotation matrix for the frame biases. The new series of nutation angles will be used for preparation of our suggestion to improve the nutation theory.

- **Routine analysis**

During 2015–2016 the routine data processing was performed with the ARIADNA software using the least-squares method with rigid constraints.

The SAI–VNIIFTRI AC operationally processed the 24-hour and Intensive VLBI sessions. The forming of databases of the VLBI sessions and processing of all sessions is fully automated. The EOP series vnf_2015.eoxy, vnf_2016.eoxy, vnf_2015.eopi, and vnf_2016.eopi were calculated. These series were computed with the catalog VTRF2015 of station positions and velocities. SINEX files were generated for all 24-hour sessions.

The weighted mean (WM) and weighted root mean square (WRMS) UT1 differences between SAI–VNIIFTRI and BKG, IAA, USNO estimates from all Intensives sessions are shown in Figure 1 and from 24-hour solutions are shown at Figure 2.

They were calculated using the formulas:

$$WM_j = \sum_{i=1}^{N} \frac{(\mathrm{UT1}_{AC_{j,i}} - \mathrm{UT1}_{AC_{SV,i}}) p_{j,i}}{\sum_{i=1}^{N} p_{j,i}}$$

$$WRMS_j = \sqrt{\frac{\sum_{i=1}^{N} \left(\mathrm{UT1}_{AC_{j,i}} - \mathrm{UT1}_{AC_{SV,i}} - WM_j\right)^2 p_{j,i}}{\sum_{i=1}^{N} p_{j,i}}}$$

where

$$p_{j,i} = \frac{1}{\sigma^2_{AC_{j,i}} + \sigma^2_{AC_{SV,i}}}$$

are the weights of UT1 differences. $\mathrm{UT1}_{AC_{j,i}}$ are the estimates of the UT1 from AC_j, where $j =$ BKG, IAA, USNO and $\mathrm{UT1}_{AC_{SV}}$ the same from AC SAI-VNIIFTRI, respectively, and $\sigma_{AC_{j,i}}$ and $\sigma_{AC_{SV,i}}$ denote their formal uncertainties.

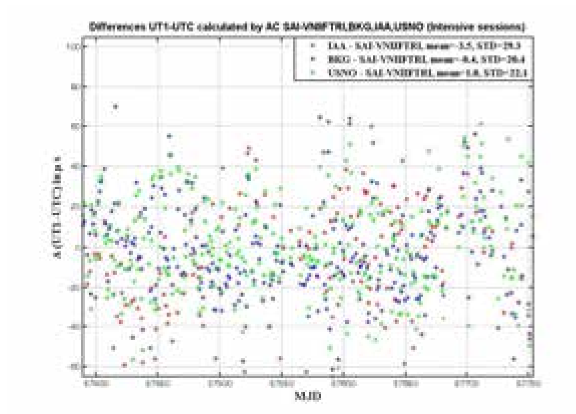

Fig. 1 Differences of the BKG, IAA, and USNO with the SAI–VNIIFTRI estimates of UT1 based on the solutions for the Intensive sessions.

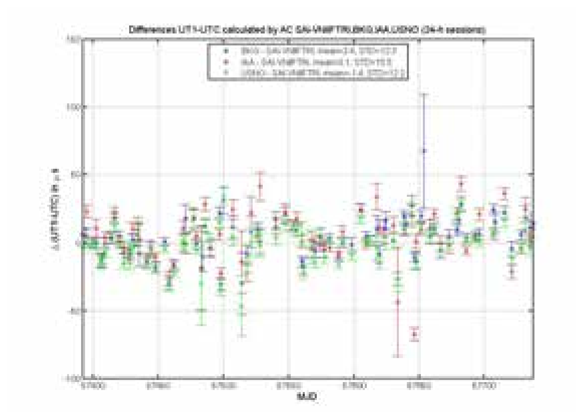

Fig. 2 Differences of the BKG, IAA, and USNO with the SAI–VNIIFTRI estimates of UT1 based on the solutions for the 24-hour sessions.

In processing 24-hour sessions, ARIADNA normally uses the a priori station coordinates from the catalog VTRF2015. If they are the estimation parameters then no-net-translation and no-net-rotation constraints are applied for selected stations. Solution for the TSUKUB32 antenna gives very large correction for the catalog position: $\Delta x = 0.047 \pm 0.013, \Delta y = -0.031 \pm 0.010, \Delta z = -0.030 \pm 0.022$. The TSUKUB32 antenna is used for UT1 estimation from the Intensive sessions. To avoid shift of the UT1 estimates from incorrect the TSUKUB32 antenna position the last was corrected for the above values.

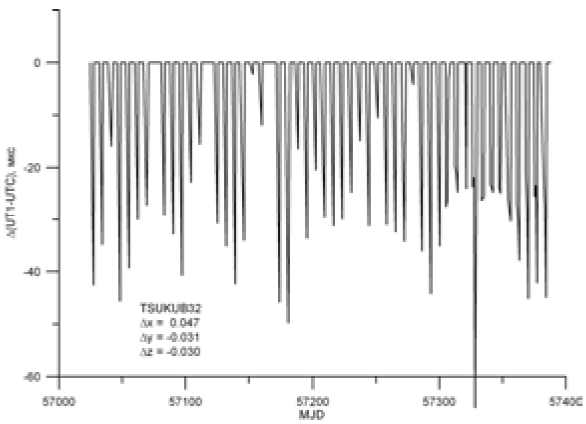

Fig. 3 Difference between UT1–UTC from two solutions (with catalog and corrected positions of the TSUKUB32 antenna) from the Intensive sessions.

Difference between UT1–UTC from two solutions (with catalog and corrected positions of the TSUKUB32 antenna) is shown in Figure 3. There is a systematic shift in the calculated value of UT1–UTC of the order of 20 μs.

4 Future Plans

- Continuing investigations of VLBI estimation of EOP, station coordinates, source coordinates and their variability.
- Improvement of the ARIADNA software for processing of the GNSS troposphere zenith delays.

References

1. N.S. Kardashev, V.V. Khartov, V.V. Abramov et al. "RadioAstron" - A telescope with a size of 300 000 km: Main parameters and first observational results. *Astronomy Reports*, 57(3), 153–194, 2013.
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IVS SHAO Analysis Center 2015–2016 Biennial Report

Guangli Wang, Minghui Xu, Zhibin Zhang, Shuangjing Xu, Li Guo, Bo Zhang, Zhihan Qian, Liang Li

Abstract This report presents the routine work and the research work carried out at SHAO VLBI Analysis Center (AC) during 2015 and 2016. The SHAO AC continues the routine VLBI data analysis of IVS 24-hour geodetic/astrometric sessions and takes the responsibility of analyzing the CVN data. We investigated structure effects in geodetic VLBI, in terms of demonstrating source structure effect at the level of each individual observable, deriving structure index from geodetic sessions without making images, deriving source structure from delays, and studying the impact of structure effects. We used the archived dual-band observations from VERA to study the atmosphere fluctuation and made a proposal for new observations by VERA to better investigate it. The VGOS antenna in Shanghai was under construction and was expected to make trial observations in late 2017.

1 General Information

The SHAO VLBI Analysis Center is located at the Shanghai Astronomical Observatory (SHAO), Chinese Academy of Sciences, China. It is a part of an astrometry research group in the Department of Astro-Geodynamics at SHAO. Some staff members are from the VLBI application in the Chinese deep space mission. We are processing the Chinese VLBI Network (CVN) data and IVS 24-hour routine sessions and one-hour Intensive UT1 sessions to provide our results and investigate some interesting topics in VLBI.

SHAO, Chinese Academy of Sciences

SHAO Analysis Center

IVS 2015+2016 Biennial Report

2 Activities during the Past Two Years

The SHAO Analysis Center analyzed all the IVS sessions by using the Calc/Solve and the nuSolve software packages, and ten CVN sessions (including solving ambiguity and determining the ionospheric effect from dual-band data). We provided VLBI products, i.e., EOP, CRF, and TRF, for the Chinese EOP Services. We investigated source structure effects in geodetic VLBI and attempted to correct source structure effects in data analysis.

3 Current Status

- Closure delay is the sum of delay observables over closed triangles. Closure delay is independent of atmospheric effects and clocks, and captures information of source structure. Figure 1 shows closure delays of six triangles with one common baseline, BADARY–WESTFORD. The six stations in these six triangles are those stations in Europe, which are located in between baseline BADARY–WESTFORD. Note that BADARY–WESTFORD is the longest baseline in these triangles. The two peaks far away from zero with this systematical pattern are unlikely due to measurement noise, but can be well explained by source structure effect. We further explored the observable of closure delay to detect source structure of 0642+449 with two equally-bright components separated by half a milliarcsecond. The result of this study was published in Xu et al. (2016). Closure delay can serve as an indicator of the magnitude of structure effect of each individual source and as a criterion to evaluate the performances of structure models, no matter how they are derived.

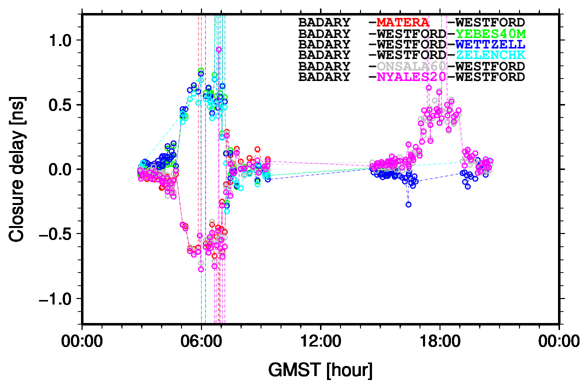

Fig. 1 Closure delays of triangles with BADARY and WESTFORD and one of the six European stations.

- Structure index (Fey & Charlot 1997) is used to classify radio sources in the sense of compactness of radio source. For example, a radio source with a structure index of 1 is considered to be compact and one with a structure index of 4 is considered to be much extended. The traditional way of calculating structure index is based on images of sources. One has to obtain an image of the source by standard imaging process and then to calculate the structure delays on each grid over the *uv* plane with the size of the Earth. The structure index is related to the median value of the structure delays of all these possible grids. We demonstrated the correlation of closure delays and structure index and proposed a method to derive structure index from closure quantities. By applying this method, one does not need to make images anymore. The historical VLBI data will provide us a great amount of information about structure index even if we do not make use of them to make images.
- We attempted to develop a method of correcting structure effects independent of calibration in imaging and the impact of structure effects on geodetic VLBI since we may expect to correct source structure effect independent of images. We referred to the method as forward modeling. It works in an iterative way: (1) closure phases of small triangles with longest baseline lengths shorter than a certain value, such as 2,000 km depending on the structure scale of the interested source, are used to determine the relative position and the flux density ratio of two components based on the model of structure phase in Charlot (1990); (2) closure phases of triangles with larger baseline lengths are gradually added and used to test the obtained multicomponent model by the previous step until a significant mismatch between modeled closure phases and observed closure phases occurs; (3) another component is proposed and added to the previous model, and then repeat the second step. The whole procedure will stop when all the closure phases were exploited.
- A three-component model was determined for 3C371, and a detailed comparison was done with imaging results of the visibility from the same observations. The impact of source structure was preliminarily studied by using the derived three-component model of 3C371. The rms residual of source 3C371 was reduced by 1 ps (Xu et al., 2017)
- We have been investigating the systematic variation of Celestial Reference Frame, which was identified first by the GSFC VLBI group. The pattern is that the southern sources appear with lower declinations, determined from all historical data till recent years, compared to the catalog of ICRF2. We have some clues for this phenomenon at the moment. We are also processing Q-band VLBI observations made by VLBA from November 2014 to May 2016, and K-band observations.
- We have been working on building a VGOS antenna in the area of the Tianma 65-meter antenna. The construction permission by related administrations has just been worked out and the constructing contract for the company also went through. Now the pillar is under construction. Within the great effort of several members in our group, this new antenna should be able to do trial observations in late 2017.
- After submitting the SINEX products for the ITRF2014, we continued the evaluation of the ITRF2014P and submitted our report to Dr. Zuheir Altamimi.

Fig. 2 Group photo of the SHAO AC members taken in front of our main building.

- The comparison of theoretical delays for different software packages organized by Onsala observatory was participated at the SHAO AC.

4 Staff

During 2015 and 2016, the staff of the SHAO AC contains one consultant, a group leader Dr. Wang, five employees, and one PhD student, shown in Table 1 and in Figure 2.

Table 1 Staff members and the main tasks.

Dr. Guangli Wang	Group lead, VGOS project, data analysis
Dr. Minghui Xu	Data analysis and imaging
Dr. Li Guo	Positioning and data analysis
Dr. Bo Zhang	Phase referencing and imaging
MSc. Shuangjing Xu	Imaging and data analysis
Prof. Zhihan Qian	Consulting
Dr. Liang Li	Data analysis and CRF

5 Future Plans

We will mainly focus on data analysis of observations made by VGOS antennas in China. There should be about four 13-meter antennas in China to conduct such observations. We will continue the current study of the systematical variation in CRF, source structure effects, and data analysis of VLBI observations at high frequencies. A proposal was made to VERA to get dual-beam observations to study the atmosphere effect. We will continue our study of determining Solar acceleration from VLBI as long as we work out the systematic variation in CRF, since we suspect this variation will affect the estimation of the Solar acceleration.

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Tsukuba VLBI Analysis Center

Takahiro Wakasugi [1], Tetsuya Hara [1,2]

Abstract This report summarizes the activities of the Tsukuba VLBI Analysis Center during 2015 and 2016. The weekend IVS Intensive (INT2) sessions were regularly analyzed using the *c5++* analysis software.

1 Introduction

The Tsukuba VLBI Analysis Center, located in Tsukuba, Japan, is operated by the Geospatial Information Authority of Japan (GSI). One of our major roles as an Operational Analysis Center is to regularly analyze the weekend IVS Intensive (INT2) sessions using the fully automated VLBI analysis software *c5++* developed by the National Institute of Information and Communications Technology (NICT) [1]. It should be noted that a UT1–UTC (= dUT1) solution becomes available within a few minutes after the end of the last scan of a session. A 10 Gbps dedicated link to the SINET5 operated by the National Institute of Informatics (NII) and several process management programs make it possible to derive the solutions rapidly. In addition, we started the Ishioka–Wettzell baseline observations called Q-Intensives from October 2016 in order to validate dUT1 solutions of the new baseline.

1. Geospatial Information Authority of Japan
2. Advanced Engineering Service Co., Ltd.

Tsukuba VLBI Analysis Center

IVS 2015+2016 Biennial Report

2 Component Description

2.1 Analysis Software

C5++, which is an analysis software for space geodesy including SLR, GNSS, and VLBI, is officially used to provide a dUT1 solution in regular INT2 sessions.

Calc/Solve has been in use throughout from the early days of VLBI work at GSI. It is used for the analysis of Japanese domestic VLBI observations (JADE) and Asia-Oceania VLBI Group for Geodesy and Astrometry (AOV) sessions in its interactive mode and for global analysis in batch mode. In 2016, we confirmed that *νSolve* released by the GSFC VLBI group worked well as a substitute for the legacy user interface of the interactive mode of *Solve*. We will use it for regular sessions starting in 2017.

2.2 Analysis Center Hardware Capabilities

c5++, *Calc/Solve*, and *νSolve* are installed on several general purpose and commercially produced Linux computers (Table 1). Two 3 TB HDDs are used for storing many VLBI data files such as Mark III databases. One is used as main storage and mirrored by the other regularly.

3 Staff

The technical staff of the Tsukuba Analysis Center are:

Table 1 Analysis Center hardware capabilities.

Number of servers	five for VLBI analysis (*c5++*, *Calc/Solve*, and *νSolve*)
Operating System	CentOS version 5.4, 5.5, 6.5, and Red Hat Enterprise Linux 6.3
CPU	Intel Xeon X3360 @2.83GHz quad CPU, Intel Xeon X5687 @3.60GHz quad CPU x 2 Intel Xeon E3-1270V2 @3.50GHz quad CPU
Storage capacity	3 Tbytes x 2

- **Takahiro Wakasugi**: correlator/analysis chief, management.
- **Tetsuya Hara** (AES): correlator/analysis operator, software development.

4 Analysis Operations

4.1 IVS Intensive for UT1-UTC

There were 104 and 106 IVS Intensive sessions analyzed at the Tsukuba Analysis Center in 2015 and 2016, respectively. The dUT1 results were submitted as gsiint2b.eopi to the IVS Data Center (Table 2). Only the dUT1 parameter was estimated with station positions fixed to a priori values. For the Tsukuba station after the 2011 Off-the-Pacific-Coast-of-Tohoku Earthquake, the position correction of the non-linear postseismic motion provided by NASA/GSFC was used. The Tsukuba–Wettzell baseline and several other baselines were analyzed. The observed data at Wettzell are e-transferred to the Tsukuba Correlator in near real-time with the Tsunami UDP protocol. The correlated data are rapidly analyzed by *c5++* as soon as all of the correlator outputs are available, and then a dUT1 solution is derived and submitted. The dUT1 solution becomes available at the IVS Data Center immediately after the session. The processes from data transfer to submission of the solution are fully automated and done by unmanned operation.

Table 2 Intensive sessions analyzed at the Tsukuba Analysis Center.

2015	Baseline	# of sessions	Average of dUT1 sigma
Intensive 2	TsWz	99	7.04 μsec
	KbWz	2	14.00 μsec
Intensive 3	NyShTsWnWz	1	4.92 μsec
	NyTsWnWz	2	5.93 μsec
Total		104	7.13 μsec

2016	Baseline	# of sessions	Average of dUT1 sigma
Intensive 2	TsWz	100	8.50 μsec
	IsWz	27	10.12 μsec
Total		115	8.84 μsec

Since 42 out of 199 Tsukuba–Wettzell baseline analyses had some sort of problem in the observed data or trouble at the stations, the automated analyses failed. In the other 157 sessions, we succeeded in the rapid analysis with low latency. Figure 1 shows the cumulative distribution of 103 Tsukuba–Wettzell sessions from January 2015 to April 2016 with respect to the latency within which dUT1 solutions of the sessions were derived. About 90% of them completed analysis within four minutes after the end of the last scan, and all of them completed within six and half minutes. Though the latency increased slightly because of the decrease of the transfer rate caused by the replacement of a PC in Wettzell after May 2016, we still keep low-latency analysis completion, i.e., 80% of sessions completed within 15 minutes.

The ending time of IVS INT2 sessions is 8:30 UT on every Saturday and Sunday. Thus, the dUT1 solution is available for users before 9:00 UT as an IVS product. Our products are utilized for more accurate dUT1 prediction by the U.S. Naval Observatory (USNO) as the IERS Rapid Service/Prediction Centre, which is responsible for providing earth orientation parameters on a rapid turnaround basis, primarily for real-time users and others needing the highest quality EOP information sooner than that available in the final EOP series.

In the last quarter of 2015, GSI analyzed three INT3 (Monday morning in UT) sessions instead of the Bonn correlator due to its maintenance. This was the first time for Tsukuba Analysis Center in four years to process multi-baseline Intensive sessions. Our automated processing software was given the capability of multi-

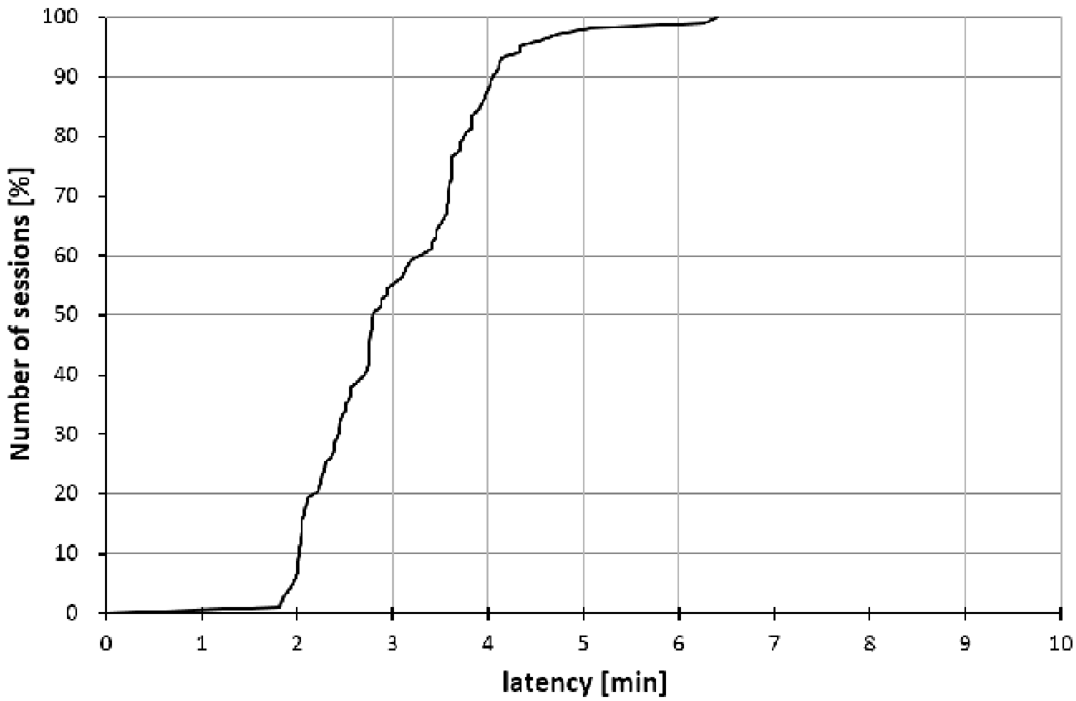

Fig. 1 The cumulative distribution of 103 Tsukuba–Wettzell sessions from January 2015 to April 2016 with respect to the latency within which dUT1 solutions of the sessions were derived.

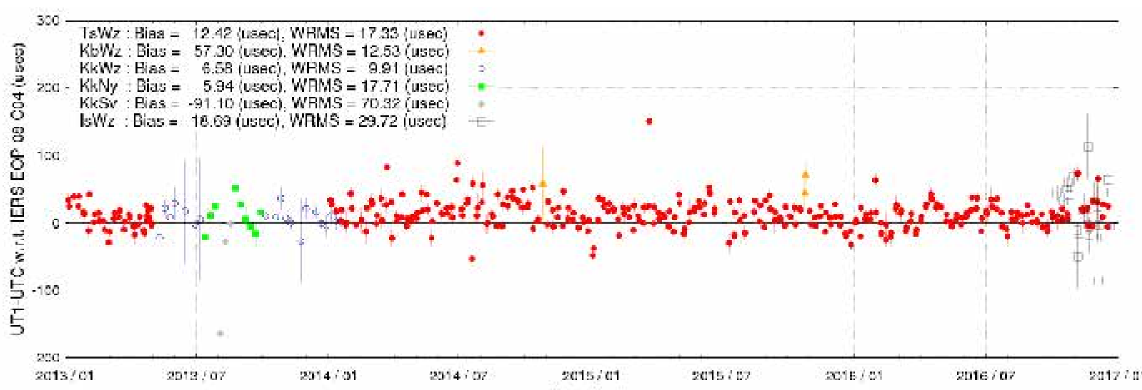

Fig. 2 The time series of UT1–UTC derived from IVS Intensives with respect to IERS EOP 08 C04. Error bars are 1 σ formal uncertainties.

baseline processing with only slight modifications, and the processing ended successfully.

Figure 2 shows the differences between the dUT1 solutions of each Intensive baseline and IERS EOP 08 C04 from January 2013 through December 2016.

4.2 IVS Intensive with Ishioka

IVS started the Ishioka–Wettzell baseline observations called Q-Intensives from October 2016 in response to ceasing operations of Tsukuba at the end of 2016. The Q-Intensives were also processed by GSI. There were some steps to establish the analysis process of this new baseline. We calculated the station coordinates of Ishioka by using the relative position to Tsukuba estimated from more than forty 24-h sessions. In conjunction with this new baseline solution, we updated the analysis software *c5++* from beta version to the release version with a new automatic ambiguity estimation strategy [2]. In addition to this, we slightly modified our correlation and analysis management programs for fully automated processing (refer to the report "Tsukuba VLBI Correlator" in this volume). Thirty-three Q-Intensive sessions were performed from October to December in 2016 in addition to the regular Tsukuba–Wettzell Intensive sessions. We started to release our new dUT1 results as gsiint2c.eopi to the IVS Data Center from the beginning of 2017.

5 Outlook

We will continue to analyze the data of the IVS INT2 sessions and submit dUT1 products with a low latency. In addition, we will try to modify our analysis process to obtain more precise results including compatibility with ITRF2014.

References

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U.S. Naval Observatory VLBI Analysis Center

Alan Fey, Nicole Geiger, Christopher Dieck, Megan Johnson

Abstract This report summarizes the activities of the VLBI Analysis Center at the United States Naval Observatory for calendar years 2015–2016. Over the course of two years, Analysis Center personnel continued analysis and timely submission of IVS-R4 databases for distribution to the IVS. During the calendar years 2015–2016, the USNO VLBI Analysis Center used the VLBI global solutions designated usn2015a, usn2015b, and usn2016a. Earth orientation parameters (EOP) based on the solutions and updated by the latest diurnal (IVS-R1 and IVS-R4) experiments, were routinely submitted to the IVS. Sinex format files based upon the bi-weekly 24-hour experiments were also submitted to the IVS.
During the 2015–2016 calendar years, Analysis Center personnel continued a program to use the Very Long Baseline Array (VLBA) operated by the NRAO for the purpose of measuring UT1–UTC. Routine daily one-hour duration Intensive observations continued using the VLBA antennas at Pie Town, NM and Mauna Kea, HI.

1 Introduction

The USNO VLBI Analysis Center is supported and operated by the United States Naval Observatory (USNO) in Washington, DC. The primary services provided by the Analysis Center are the analysis of diurnal experiments, the production of periodic VLBI global solutions for estimation of the Terrestrial Reference Frame (TRF), the Celestial Reference Frame (CRF), and Earth Orientation Parameters (EOP). The Analysis Center continued the submission to the IVS of Intensive (EOP-I) and session-based (EOP-S) Earth orientation parameters based on USNO VLBI global solutions. Analysis Center personnel maintain the necessary software required to continue these services to the IVS including periodic updates of the GSFC CALC/SOLVE software package. In addition to operational VLBI analysis, Analysis Center personnel are actively engaged in research related to future reference frames, the electronic transfer of VLBI data, and software correlation.

U.S. Naval Observatory

USNO Analysis Center

IVS 2015+2016 Biennial Report

2 Current Analysis Center Activities

2.1 IVS Experiment Analysis and Database Submission

During the 2015–2016 calendar years, personnel at the USNO VLBI Analysis Center continued to be responsible for the timely analysis of the IVS-R4 experiments, with the resulting databases submitted within 24 hours of correlation for dissemination by the IVS. Analysis Center personnel continue to be responsible for the analysis and database submission for the periodic IVS-CRF experiments. Analysis Center personnel also continued analyzing IVS Intensive experiments for use in the USN-EOPI time series and continued a new series of Intensive sessions using the VLBA antennas at Pie Town, NM and Mauna Kea, HI.

2.2 Global VLBI Solutions, EOP, and Sinex Submission

USNO VLBI Analysis Center personnel used the periodic global TRF/CRF/EOP solutions usn2015a, usn2015b, and usn2016a over the course of the 2015–2016 calendar years. Analysis Center personnel continued to submit the USN-EOPS series, which is based upon the current global solution and updated with new IVS-R1/R4 experiments. The updated EOPS series is submitted to the IVS twice weekly within 24 hours of experiment correlation and is included in the IERS Bulletin A. Analysis Center personnel also continued routine submission of Sinex format files based upon the 24-hour VLBI sessions. In addition to EOPS and Sinex series, USNO VLBI Analysis Center personnel continued to produce and submit an EOPI series based upon the IVS Intensive experiments.

2.3 νSolve for Interactive VLBI Analysis

The USNO VLBI Analysis Center fully transitioned to the use of νSolve for interactive VLBI analysis.

2.4 VLBA Intensive Experiments

During the 2014 calendar year, Analysis Center personnel continued a program to use the Very Long Baseline Array (VLBA) operated by the NRAO for the purpose of measuring UT1–UTC. Routine daily one-hour duration Intensive observations continued using the VLBA antennas at Pie Town, NM and Mauna Kea, HI. High-speed network connections to these two antennas are now routinely used for electronic transfer of VLBI data over the Internet to a USNO point of presence. Once fully operational, it is anticipated that these VLBA Intensive sessions will be scheduled as IVS-INT4 sessions and that the data will be released to the IVS for community-wide distribution.

3 Staff

The staff of the VLBI Analysis Center is drawn from individuals in the Astrometry Department at the U.S. Naval Observatory. The staff and their responsibilities are as follows:

Name	**Responsibilities**
Alan Fey	Periodic global CRF/TRF/EOP solutions and comparisons; CRF densification research; VLBI data analysis.
Nicole Geiger	VLBI data analysis; EOP, database, and Sinex submission.
Christopher Dieck	VLBI data analysis; EOP, database, and Sinex submission.
Megan Johnson	VLBI data analysis; EOP, database, and Sinex submission.

4 Future Activities

The following activities for 2017 are planned:

- Continuing the analysis and the submission of IVS-R4 experiments for dissemination by the IVS.
- Continuing the production of periodic global TRF/CRF/EOP solutions and the submission of EOP-S estimates updated by the IVS-R1/R4 experiments to the IVS.
- Continuing the submission of Sinex format files based on the 24-hour experiments.
- Continuing the analysis of IVS Intensive experiments and submission of EOP-I estimates to the IVS.
- Continuing the scheduling, analysis, and database submission for IVS-CRF and IVS-CRDS experiments.
- Continuing the post-processing and the analysis of VLBI Intensive data from the MK and PT VLBA stations.

USNO Analysis Center for Source Structure Report

Alan Fey

Abstract This report summarizes the activities of the United States Naval Observatory Analysis Center for Source Structure for calendar years 2015 and 2016.

1 Analysis Center Operation

The Analysis Center for Source Structure is supported and operated by the United States Naval Observatory (USNO). The charter of the Analysis Center is to provide products directly related to the IVS determination of the "definition and maintenance of the celestial reference frame." These include, primarily, radio frequency images of International Celestial Reference Frame (ICRF) sources, intrinsic structure models derived from the radio images, and an assessment of the astrometric quality of the ICRF sources based on their intrinsic structure.

The Web server for the Analysis Center is hosted by the USNO and can be accessed by pointing your browser to

`http://rorf.usno.navy.mil/ivs_saac/.`

The primary service of the Analysis Center is the Radio Reference Frame Image Database (RRFID), a Web accessible database of radio frequency images of ICRF sources. The RRFID contains 7,279 Very Long Baseline Array (VLBA) images of 782 sources at radio frequencies of 2.3 GHz and 8.4 GHz. Additionally, the RRFID contains 1,867 images of 285 sources at frequencies of 24 GHz and 43 GHz. The RRFID can be accessed from the Analysis Center Web page or directly at

`http://rorf.usno.navy.mil/rrfid.shtml.`

The RRFID also contains 74 images of 69 Southern Hemisphere ICRF sources using the Australian Long Baseline Array (LBA) at a radio frequency of 8.4 GHz.

Images of ICRF sources can also be obtained from the Bordeaux VLBI Image Database (BVID) at

`http://www.obs.u-bordeaux1.fr/m2a/BVID/.`

2 Current Activities

The current Analysis Center activity is maintaining the Radio Reference Frame Image Database as a Web accessible database of radio frequency images of ICRF sources.

3 Staff

The staff of the Analysis Center during 2015 and 2016 consisted of Alan L. Fey.

4 Future Activities

The Analysis Center currently has a program of active research investigating the effects of intrinsic source

U.S. Naval Observatory

USNO Analysis Center for Source Structure

IVS 2015+2016 Biennial Report

structure on astrometric position determination. Results of this program are published in the scientific literature.

The following activities for 2017 are planned:

- Continuing with the imaging and analysis of VLBA 2.3/8.4/24/43 GHz experiments.
- Maintaining the Radio Reference Frame Image Database (RRFID) as a Web accessible database of radio frequency images of ICRF sources.
- Continuing preparatory work for ICRF-3.

5 Relevant Publications

Publications of relevance to Analysis Center activities are:

- "Second Epoch VLBA Calibrator Survey Observations: VCS-II," by Gordon, D., Jacobs, C., Beasley, A., Peck, A., Gaume, R., Charlot, P., Fey, A., Ma, C., Titov, O., & Boboltz, D., 2016, AJ, 151, 154
- "The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry," by Fey, A., et. al., 2015, AJ, 150, 58
- "Relativistic Jets in the Radio Reference Frame Image Database. II. Blazar Jet Accelerations from the First 10 Years of Data (1994-2003)," Piner, B. G., Pushkarev, A. B., Kovalev, Y. Y., Marvin, C. J., Arenson, J. G., Charlot, P., Fey, A. L., Collioud, A., & Voitsik, P. A. 2012, ApJ, 758, 84
- "Characterization of long baseline calibrators at 2.3 GHz," Hungwe, F., Ojha, R., Booth, R. S., Bietenholz, M. F., Collioud, A., Charlot, P., Boboltz, D., & Fey, A. L. 2011, MNRAS, 418, 2113.
- "The Position/Structure Stability of Four ICRF2 Sources," Ed Fomalont, Kenneth Johnston, Alan Fey, Dave Boboltz, Tamoaki Oyama, and Mareki Honma, 2011, AJ, 141, 91.

Vienna Special Analysis Center Biennial Report 2015/2016

Johannes Böhm [1], Sigrid Böhm [1], Anastasiia Girdiuk [1], Jakob Gruber [1], Andreas Hellerschmied [1], Armin Hofmeister [1], Hana Krásná [1], Younghee Kwak [1], Daniel Landskron [1], Matthias Madzak [2], David Mayer [1], Matthias Schartner [1]

Abstract The main activities in 2015 and 2016 of the IVS Special Analysis Center at Technische Universität Wien (TU Wien) are related to the analysis of VLBI observations with the Vienna VLBI and Satellite Software (VieVS), for example with contributions to ITRF2014 and ICRF3, and to the correlation of VLBI raw data on the Vienna Scientific Cluster 3 (VSC-3). In terms of updates and modifications of VieVS, the observation of satellites with VLBI radio telescopes and the improvement of the scheduling part will be mentioned here with more aspects provided in the sections below.

1 General Information

The Department of Geodesy and Geoinformation (GEO) in the Faculty of Mathematics and Geoinformation of TU Wien is divided into seven research areas. One of those, the research area Höhere Geodäsie (Advanced Geodesy) with about twenty members, is focusing on satellite geodesy, interactions in the System Earth, and geodetic VLBI. Some of the group members took part in the excursion to the Geodetic Observatory Wettzell in May 2016 (see Figure 1).

1. Technische Universität Wien
2. Bundesamt für Eich- und Vermessungswesen

VIE Analysis Center

IVS 2015+2016 Biennial Report

2 Staff

Personnel at GEO associated with the IVS Special Analysis Center in Vienna (VIE) and their main research fields and activities are summarized in Table 1. The staff members are partly paid by TU Wien, and partly they are funded by the Austrian Science Fund (FWF) within several projects listed in the acknowledgements.

3 Current Status and Activities

3.1 Global Reference Frames and Earth Orientation

In 2015 we submitted to the IVS Data Centers a solution (Böhm et al., 2016 [4]) that was first used for a VLBI-only combination (Bachmann et al., 2016 [1]). In a second step, the VLBI-only combined solution was used as input for the determination of the ITRF2014. Since 2016, we have also been contributing to the ICRF3 Working Group of the International Astronomical Union (IAU) by submitting solutions based on observations from 1979 to 2016. Figure 2 depicts a systematic effect between the Vienna solution and the ICRF2. In the first place, the bias is related to new (w.r.t. the ICRF2) data from the recently built southern stations, but systematic mismodeling of the tropospheric delays could also result in a systematic shift in source declination. In order to shed some light onto the origin of this bias, we have been examining the effects of tropospheric delay modeling on source coordinates. In particular, a priori ray-traced tropospheric

Fig. 1 Staff members of the Vienna VLBI group and master students from Technische Universität Wien at the excursion to the Geodetic Observatory Wettzell in May 2016. Here, Alexander Neidhardt is explaining the new twin telescopes.

Table 1 Staff members ordered alphabetically by last name.

Johannes Böhm	Reference frames, atmospheric effects in space geodesy
Sigrid Böhm	Reference frames, Earth orientation
Anastasiia Girdiuk	Tidal effects and Earth orientation
Jakob Gruber (since 10/2016)	Correlation, vgosDB in VieVS
Andreas Hellerschmied	VieVS admin, satellite observations with VLBI
Armin Hofmeister	Ray-traced delays and VLBI analysis
Hana Krásná	Reference frames, VLBI global solutions
Younghee Kwak (until 03/2016)	Hybrid GNSS-VLBI observations
Daniel Landskron	Troposphere delay models
Matthias Madzak	Graphical user interface and special files in VieVS, Earth rotation
David Mayer	Vienna contribution to the ICRF3, scheduling
Matthias Schartner (since 10/2016)	Scheduling VLBI sessions, ringlaser

slant delays are of interest for us. Krásná et al. (2015 [9]) focused on the impact of neglected seasonal signals in the station displacement on the celestial reference frame and Earth orientation parameters (EOP). Our results revealed that there is no systematic propagation of the seasonal signal into the orientation of the celestial reference frame, but position changes occur for radio sources observed non-evenly over the year. On the other hand, the omitted seasonal harmonic signal in horizontal station coordinates propagates directly into the Earth rotation parameters causing differences of several tens of microarcseconds. In another study, Krásná et al. (2016 [10]) investigated the impact of EOP estimation on source positions for the Very Long Baseline Array Calibrator Survey (VCS) observing sessions. We found that there is a system-

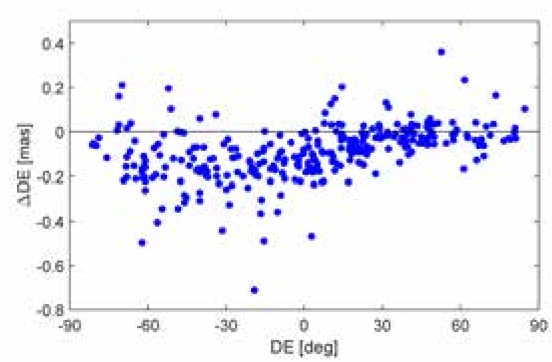

Fig. 2 Declination bias between Vienna solution (1979 to 2016) and ICRF2.

atic effect of up to one milliarcsecond in the estimated source coordinates between a solution with fixed EOP from the GNSS and a solution where the EOP are estimated in the VLBI analysis. In the past two years, we have also focused on the improved generation of high-resolution EOP time series, both from single session analysis as well as in a global solution. In particular, the focus was on 'radiational tides', which are very small oscillations. We found discrepancies in the comparison of empirical high-frequency models based on VLBI analysis with atmospheric angular momentum time series based on variations in pressure fields (provided by M. Schindelegger) (Girdiuk et al., 2016 [5]). Consequently, we had a closer look at reductions such as accounting for ocean loading effects on station coordinates.

3.2 Tropospheric Delays

In terms of tropospheric delays, we have tried to improve the current models developed at our group such as VMF1 (Böhm et al., 2006 [2]) and GPT2w (Böhm et al., 2015 [3]). On the one hand, new mapping functions are determined for discrete as well as empirical applications, referred to as VMF3 and GPT3 (not published yet). Their calculation is based on ray-traced delays calculated with the new ray-tracing software RADIATE (Hofmeister and Böhm, 2017 [8]). On the other hand, new horizontal tropospheric gradients (Landskron et al., 2016 [11]), which account for the azimuthal variation of tropospheric delays, are determined from the ray-traced delays as well. If applied a priori in VLBI analysis, the gradients have the potential of improving the accuracy of the solutions as assessed with baseline length repeatabilities.

3.3 Scheduling Developments

The scheduling module in VieVS (Sun et al., 2014 [13]) has been improved, and new features have been added in the past two years. Important new features are:

- Graphical user interface to create schedules manually or semi-manually,
- Graphical user interface to analyze schedules,
- Possibility to automatically create multiple schedules with different parametrizations,
- Improved fill-in modes,
- New optimization parameters, which can improve the schedule significantly,
- New independent checking tool, which verifies the computed schedule,
- Deeper integration of the scheduling and simulation module in the rest of VieVS, and
- Reduced runtime.

There is a new manual tool, which can be used in a very flexible way to create schedules for special purposes. It includes the possibility to select every scan by hand or to generate a schedule automatically up to a certain time. It is possible to select or deselect stations or to change optimization parameters and strategies during the schedule. In the manual mode, a list of recommended next scans is provided, which can be used to select a scan, or it is possible to manually tell every station which source to observe. Almost everything is manually adjustable such as the scan duration, the scan start time, or the optimized baselines. New parameters are used to optimize the weighting between the number of observations, the scan start time, and the sky coverage. Together with all of the other optimization parameters, it is often difficult to find a good set of parameters. Therefore, the new multi-scheduling tool was developed. It is now possible to calculate multiple schedules with different parametrizations and to automatically simulate observations and estimate the unknowns using VieVS. The accuracy of the estimated unknowns can then be used to select a good set of parameters. This scheduling tool has some basic multi-core support to reduce runtime. Reducing runtime was in general a focus during the last development phase. For a schedule with 13 stations and roughly 150 sources, the generation of the schedule is now more than five times faster. If you use the multi-scheduling tool with four cores, it is more than ten times faster.

3.4 VLBI Observations to Satellites

VLBI observations of satellites being equipped with multiple space-geodetic techniques provide promising opportunities for the realization of inter-technique ties in space. Therefore, VieVS was upgraded with dedicated features for the scheduling and analysis of observations to satellites. The scheduling module was extended with functions to create fully realistic VEX-formatted schedule files capable of running experiments (Hellerschmied et al., 2015 [6]). The analysis part of VieVS was upgraded with a near-field delay model and supports delay observables from satellite observations as input. Hence, near-field observations can now be used by all available analysis means analogously to classical observations to quasars. Major research activities in this field were carried out in cooperation with the University of Tasmania (UTAS, Australia) and the AuScope VLBI network. In 2015 a series of experiments with VLBI observations of GNSS satellites on the baseline Hobart-Ceduna were utilized to establish a processing chain for satellite observations. The workflow is based on VieVS, providing the scheduling and analysis features, and on DiFX, being used for correlation. First results are described by Plank et al. (2017 [12]). In November 2016, we intensively collected observation data of the Chinese APOD CubeSat (Tang et al., 2016 [14]) which can be considered as a prototype for future co-location satellite missions. The Australian AuScope antennas were used for these challenging experiments (Hellerschmied et al., 2017 [7]). Data analysis is currently ongoing. Furthermore, we provided observation schedules for numerous test observations to satellites (mainly GNSS and APOD) for the observatories in Wettzell (Germany), Onsala (Sweden), and Medicina and Sardinia (both in Italy).

3.5 Correlation

Geodetic VLBI correlation is a new challenge in the portfolio of our current activities. So far, we have implemented the Distributed FX (DiFX) software correlator and Haystack Observatory Postprocessing System (HOPS) on our working environment to correlate VLBI signals. We are capable of running DiFX and HOPS on several of our local machines and on the Vienna Scientific Cluster 3 (VSC-3), which is a high performance computing system located at the TU Wien. VSC-3 consists of 2020 nodes, each equipped with two processors (Intel Xeon E5-2650v2, 2.6 GHz, eight cores from the Ivy Bridge-EP family) and internally connected with an Intel QDR-80 dual-link high-speed InfiniBand fabric (see Figure 3). With this top-rated high performance computer system we are able to process a vast amount of VLBI data. To bridge the gap between the correlator output and standard VLBI analysis software we are developing a tool to convert the correlator output to VGOS database format.

Fig. 3 The high performance computing system at the Vienna Scientific Cluster.

3.6 Development of VieVS

Many updates of VieVS are related to the activities mentioned above, for example with respect to the observation of satellites. Consequently and also considering future plans, VieVS is now the abbreviation for the *Vienna VLBI and Satellite Software*. The documentation of VieVS can be found on a Wiki at http://vievs.geo.tuwien.ac.at/. We have continued organizing VieVS User Workshops with the 6th and

7th workshops held in September 2015 and 2016, respectively, and we plan to host the 8th VieVS User Workshop in September 2017.

4 Future Plans

A major focus will be on the correlation of VLBI data on the Vienna Scientific Cluster 3 (VSC-3) as well as on the determination of multiband delays with HOPS. Moreover, we plan to have a closer look into VGOS data. Of course, we will continue our work on reference frames (contribution to ICRF3), Earth orientation parameters, and the observation of satellites with VLBI radio telescopes.

Acknowledgements

We are very grateful to the Austrian Science Fund (FWF) for supporting our work by projects P 25320 (RADIATE VLBI), M 1592 (Hybrid GPS-VLBI), I 1479 (ASPIRE), I 2204 (SORTS), and T 697 (Galactic VLBI). In terms of correlation, we would like to acknowledge the support by the team of the Vienna Scientific Cluster 3 (VSC-3) and by Jamie McCallum from the University of Tasmania.

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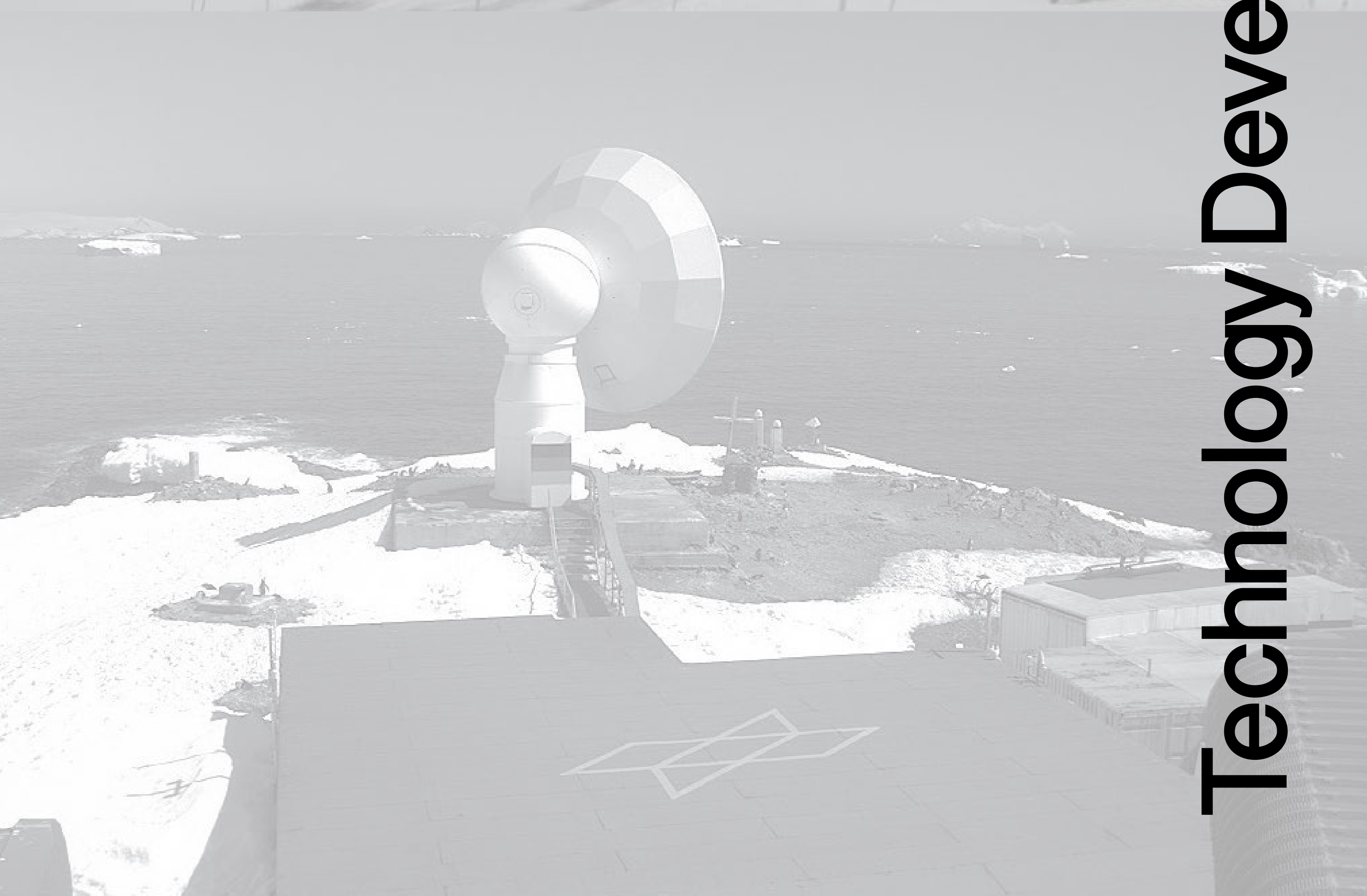
Technology Development Centers



Canadian VLBI Technology Development Center Report

Bill Petrachenko, Anthony Searle

Abstract The Canadian VLBI Technology Development Center (TDC) is involved in a number of activities contributing to the realization of the VLBI Global Observing System (VGOS).

1 Activities during 2015 and 2016

The Canadian TDC is sponsored by the Canadian Geodetic Survey (CGS) of Natural Resources Canada (NRCan). It is focused on encouraging the realization of VGOS. This is done primarily by Bill Petrachenko (who is past IVS Technology Coordinator, is past chairman of the VGOS Technical Committee (VTC), and is currently a member of VPEG, the VGOS Project Executive Group) and Anthony Searle of NRCan. In collaboration with others, activities focused on the following areas:

- Development of novel scheduling strategies that involve fixed source switching intervals. These schedules perform very well for larger networks (greater than about 12 stations) and are tolerant of stations leaving and joining the network as circumstances change.
- Development of criteria for selecting radio sources for broadband observing.
- Investigation of the use of DBE-based pulse cal detectors as an added real time tool for evaluating station performance.
- Initiation of a dialog to investigate the possibility of installing low power VGOS signal sources on Galileo II satellites.
- Investigation of the feasibility and benefits of the use of a VGOS frequency mode that involves continuous frequency coverage across the full VGOS 2–14 GHz input range, i.e., without regard to the restriction of the use of four 1-GHz bands.

The Canadian TDC maintains close ties with the Dominion Radio Astrophysical Observatory (DRAO) of the National Research Council of Canada (NRC). DRAO is involved in a number of activities that have potential applications to the IVS.

- Digital signal processing including development of correlators, beam formers, and systems for pulsar processing.
- Fabrication of a light, stiff, and cost effective 15-m off-axis Gregorian top-fed composite antenna.
- Development of focal plane arrays.

2 Future Plans

The Canadian TDC plans to continue to actively encourage the realization of VGOS.

Canadian Geodetic Survey, Natural Resources Canada

Canadian VLBI Technology Development Center

IVS 2015+2016 Biennial Report

GSFC IVS Technology Development Center Biennial Report Submission

Ed Himwich, John Gipson, Dave Horsley, Mario Bérubé

Abstract This report summarizes the activities of the GSFC Technology Development Center (TDC) and describes plans for the future. The GSFC TDC develops station software including the Field System (FS), station monitoring software, scheduling software (*sked*), hardware including tools for station timing and meteorology, scheduling algorithms, and operational procedures. It provides a pool of individuals to assist with station implementation, check-out, upgrades, and training.

1 General Information

The GSFC IVS Technology Development Center (TDC) develops hardware, software, algorithms, and operational procedures. It provides manpower for station visits for training and upgrades. Other technology development areas at GSFC are covered by other IVS components such as the GSFC Analysis Center. The current staff of the GSFC TDC consists of John Gipson, Ed Himwich, Dave Horsley, and Mario Bérubé. The remainder of this report covers the status of the main areas supported by the TDC.

2 Field System

The GSFC TDC is responsible for development, maintenance, and documentation of the Field System (FS) software package. The FS provides equipment control at VLBI stations. It interprets the `.snp` schedule and `.prc` procedure files (both as prepared by *drudg* from the `.skd` schedule). The FS controls the antenna, data acquisition hardware, and related ancillary equipment needed for making VLBI measurements. All major VLBI data acquisition backends are supported. The FS is customizable to allow it to control station specific equipment. It is used at almost all of the IVS Network Stations (more than 35) and also at many stations that perform VLBI only for astronomical observations. The only major VLBI facilities not using it are the LBO and VERA.

There are two major branches of the FS, currently — the "main" branch, which is used for most operational observing, and the "VGOS" branch, which is used in the operational test observations at VGOS stations. In the main branch, there were three major releases of the FS (9.11.7, 9.11.8, and 9.11.17) during this period and two minor releases (9.11.18 and 9.11.19). Full details can be found in the FS release notes. The most significant changes were:

- Support for the Mark 5C and FlexBuff recorders running the *jive5ab* control program. This allows support for recording VDIF formatted data for systems with FiLa10G modules.
- Support for the DBBC DDC personality version v105E/F, which supports up to 2 Gbps data rates.
- Support for the DBBC PFB personality, which supports data rates up to 4 Gbps. Support for the PFB personality only covers non-continuous calibration at this time.
- Unification of station SNAP procedures for all supported DBBC personalities and calibration schemes. As a result, it is no longer necessary

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IVS 2015+2016 Biennial Report

to have different procedure libraries for different configurations. This change relies heavily on the new *if* command.
- New *if* command to allow conditional execution of commands. The number of conditions currently supported for testing is limited to those that help to implement the unification of DBBC SNAP station procedures, but this number can easily be increased in the future.
- Improvements to the *HOLOG* program to make it more useful for other non-holography measurements.
- The new *fesh* and *plog* utilities to automate fetching/*drudg*ing of IVS schedules and pushing logs to the IVS Data Centers, respectively.

In the VGOS branch of the FS, there was ten minor releases (9.12.2-9.12.11) during this period. The most significant changes were:

- Support for Mark 6 recorders.
- Support for initially one, and then two, FiLa10Gs in *FMSET*.
- Support for an updated RDBE server, including VDIF epoch control/monitoring and attenuation control.
- Updated re-sync features for RDBEs.

In addition other projects were underway. These include:

- Unified Patriot 12-m (GGAO) and ISI 12-m (Kokee Park) antenna interface code. This allowed a common code base to be used for the two very similar Antenna Control Units (ACUs). Several improvements were implemented that supported both ACUs.
- An initial version of the new Telegraf-InfluxDB-Grafana (TIG) monitoring, data archiving, and display system was developed. This allows an operator to view the long- and short-term trends of station systems, which will assist in the early detection and troubleshooting of problems. In the future, these tools will also enable automated alerts and assist remote monitoring. TIG was developed at the GGAO station. Documentation was written for the system for users in the greater VLBI community and released to a set of stations for testing.
- Support for NMEA standard wind sensors.

2.1 Plans for Next Year

Several other improvements are expected in future releases, including:

- Support for continuous calibration with the DBBC PFB personality.
- Support for chopper-wheel and hot/cold load calibration methods.
- Implementation of a publication/subscription model for FS display, log, and error report output.
- Use of eRemoteControl for remote operation.
- A complete update to the documentation and conversion to a more modern format that will be easier to use and maintain.
- Conversion of the FORTRAN source to use the *gfortran* compiler, which will enable use of the source level debugger, *gdb*, for development and field debugging.
- Support for 64-bit Linux OSs.
- *Chekr* support for Mark 5A and Mark 5B systems.
- FS Linux 10, based on Debian *Stretch*.
- Support for periodic firing of the noise diode during observations.
- Completion of the VEX2 standard and implementation of it.

3 *Sked* and *Drudg*

The GSFC TDC is responsible for the development, maintenance, and documentation of *sked* and *drudg*. These two programs are very closely related, and they operate as a pair for the preparation of the detailed observing schedule for a VLBI session and its proper execution in the field. In the normal data flow for geodetic schedules, first *sked* is run at the Operation Centers to generate the `.skd` file that contains the full network observing schedule. Then stations use the `.skd` file as input to *drudg* for making the control files and procedures for their station. Catalogs are used to define the equipment, stations, sources, and observing modes which are selected when writing a schedule with *sked*.

Changes to *sked* and *drudg* are driven by changes in equipment and by feedback from the users. The following summarizes some of the important changes to these programs during 2015—2016 and plans for the future. This list includes only the most important bugs which were found and fixed over this period. A more complete summary of the changes can be found in the change_log.txt files associated with *sked* and *drudg*.

3.1 *Sked* Changes

- Combination of the experimental ‘broadband’ version of *sked* with the standard version. There is a new $BROADBAND section. Each line contains the name of a station, the bandwidth of each band, the data rate, and the sink rate (the rate that data can be written to disk). *Sked* uses this information to compute approximate values for the SNR. If the data rate is larger than the sink rate, *sked* allows extra time to write the data to disk before the next scan starts.
- Recognition of many more kinds of recorders and racks, e.g., Mark 5c, Mark 6, FlexBuff, DBBC, RDBE, etc.
- For short sessions, such as Intensives, printing out of required media in Gbytes instead of Tbytes.
- New *Fill* command. Previously an antenna would stop observing as soon as it reached its SNR target. It would then move to the next commanded source and wait until all of the other antennas for that scan were on source. This meant that there was a fair amount of idle time. The *Fill* command is executed once a schedule is done. *Sked* will go through the schedule and, for each scan, increase the observing time of each station as much as possible while making sure that it can arrive at the next scan on time. This has the effect of reducing idle time and increasing observation time.
- *Group* command. This command allows the user to specify groups of sources that can be observed sequentially. This might be used, for example, in astrometric VLBI where you want to observe several near-by sources.
- Fix of a bug that occurred if the first scan in the schedule was near the boundary of “W” (counter-clock-wise) and neutral sections.
- Fix of a bug in tag-along mode. The previous version assumed that the tag-along stations always started in the neutral cable wrap.

3.2 *Drudg* Changes

- Recognition and support for many more kinds of recorders and racks, e.g., Mark 5C, Mark 6, FlexBuff, DBBC, RDBE, etc.
- Setting of the Rack and Recorder types to ‘None’ if they were unrecognized.

3.3 Catalog Changes

The *sked* catalogs were updated during 2015—2016 to reflect the new stations coming on line — RAEGYEB, KOKEE12M, WETTZ13S, WETTZ13N, ISHIOKA, and IRBENE — or older stations that observed in IVS sessions, such as DSS34 and DSS36.

The catalogs were also modified to reflect equipment changes as more and more stations switched from analog to digital equipment.

3.4 Plans for Next Year

Plans for next year include the following:

- We will update the *sked* catalogs as new stations come on line or as equipment changes.
- We will modify the *sked* catalogs to support VEX2.
- We will support VEX2 files for both *sked* and *drudg* if and when they become available.
- We will convert *sked* to compile using a freely available compiler such as *gfortran*.

MIT Haystack Observatory Technology Development Center

Chet Ruszczyk, Ganesh Rajagopalan, Chris Eckert, Russ McWhirter, Pedro Elosegui, Arthur Neill

Abstract Technology development activity at MIT Haystack Observatory was focused on the following areas in 2015–2016: (1) KPGO 12-m Signal Chain, (2) calibration system's CDMS, (3) VGOS-compliant signal chain backend R2DBE, and (4) updates to the Mark 6.

1 KPGO 12-m VGOS Signal Chain

MIT Haystack Observatory (MIT/HO) has been responsible for the design, fabrication, deployment, and commissioning of the signal chain for the new KPGO 12-m VGOS system at Kokee Park, HI. In January 2016 the signal chain, which is comprised of three separate sub-systems — Frontend (FE), Backend (BE), and Calibration (VCS), was deployed, and the commissioning phase was completed. Reports on the step-by-step progress are available on the KPGO (Kokee Park Geophysical Observatory) blog at https://space-geodesy.nasa.gov/blogs/KPGO/index.html.

The FE contains the very sensitive low-noise electronics and QRFH feed, which were integrated with the Intertronics Solutions Inc. 12-m antenna. The system equivalent flux density was measured to be $<$ 2,500 Jy. The FE includes all supporting infrastructure (e.g., networking, power supply distribution, and monitor/control) necessary to operate the dual-linearly polarized cryogenic receiver. The calibration antenna unit (Section 2) provides the phase and noise calibration signals that are injected directly into the frontend to provide for instrumental delay and gain correction in post-correlation processing. Within the frontend the signals out of the cryogenic Dewar are amplified to drive the microwave-over-fiber link that is used to transmit the higher frequency of the spectrum to the BE. To conserve dynamic range in the link, the RFI-afflicted S-band portion of the frontend frequency range is sent separately over a coaxial downlink, which possesses significantly more dynamic range in order to be able to support observing in this frequency band. A block diagram of the signal chain FE and a photograph of the KPGO 12-m focal point can be found in Figure 1 and Figure 2, respectively.

The BE receives and distributes the microwave signals downlinked from the FE for further processing. A block diagram of the BE and a photograph of the sub-system in the KPGO control room are shown in Figure 3 and Figure 4, respectively. The low- and high-band signals from the FE are split and fed into four independently tunable 2—14 GHz Up-Down Converters (UDCs). The UDCs are currently equipped with filters for the second Nyquist zone and provide access from 2—13.5 GHz. To access the final 512 MHz of the VGOS range, 13.5—14 GHz, a filter for the third Nyquist zone will be required. The UDC supports 2.5-GHz baseband output with LO tuning resolution of 10 KHz to accommodate compatibility with other VGOS frequency conversion schemes.

In the KPGO implementation, 512-MHz Nyquist zone filters are incorporated in the UDCs to support the sample rate of the RDBE-G (ROACH Digital BackEnd-Geodetic) (1024 MHz). Following the polyphase filter bank (PFB) processing by the RDBE-G, the digitized data are transmitted over standard 10G Ethernet and recorded onto disk modules of a Mark 6

MIT Haystack Observatory

Haystack Technology Development Center

IVS 2015+2016 Biennial Report

recorder. The Mark 6 is capable of either continuous recording of a sustained 4 Gbps per disk module or 30-second bursts of 8 Gbps onto a single disk module, assuming the ratio of 50% being on source and another 50% slewing to the next source.

2 VGOS Calibration System

MIT/HO has developed a calibration system to address the VGOS challenge of 4 picoseconds uncertainty in the group delay observable. The new VGOS Calibration System (VCS) incorporates a Cable Delay Measurement Sub-system (CDMS) with upgraded versions of the existing noise and phase/delay calibration sub-systems. Components of the VCS are located in both the BE and FE of the VGOS Signal Chain (SC). The BE houses the CDMS Ground Unit (CDMS-GU), and the FE houses the Calibration Antenna Unit (Cal-AU), which contains the phase calibration generator, the noise diode, and the CDMS Antenna Unit (CDMS-AU) (Figure 5).

2.1 Cable Delay Measurement Sub-system (CDMS)

The purpose of the CDMS is to measure variations of the delay in the cable carrying the reference frequency from the Hydrogen maser to the phase calibration generator. This is needed because these variations are included in the total VLBI delay but are not experienced by the quasar signal path and thus must be removed to obtain accurate geometric delays.

A significant source of these variations, in addition to thermal changes, is mechanical stress on the reference frequency cable imparted by the motion of the antenna.

On time scales relevant to geodetic observations the CDMS is designed to meet the following delay stability requirements (Allan standard deviation):

- 1.8e-14 at 30 s
- 5.5e-15 at 100 s
- 9.0e-16 at 600 s
- 1.0e-16 at 50 min

The CDMS ground sub-system is based on Software Defined Radio (SDR) and was developed and deployed at KPGO to address this requirement.

The initial design of the CDMS, deployed at KPGO, provides correction for transmission of the reference frequency over a coaxial cable. A subsequent modification to the design allows for support of optical fiber in place of the coax, but it is presently supplied for research purposes only and requires a different version of the Cal-AU CDMS board.

3 Upgrade from RDBE-G to R2DBE-G

A digital backend (DBE) based on the ROACH2 is being developed at MIT/HO to extend the performance and cost advantages of digital processing using commercially available hardware from the CASPER collaboration.

The ROACH2 DBE leverages the ADC code base from the Event Horizon Telescope R2DBE (ROACH Version 2 Digital BackEnd) and improves on the ROACH1 DBE by processing two inputs of 2,048 MHz bandwidth, compared to 512 MHz previously, Figure 5. The design uses both VHDL and CASPER blocks to maximize performance and reduce design time. The CASPER filterbanks channelize the input signals, which are then re-quantized to two bits, and the data are output in complex format in standard VTP protocol (UDP / Packet serial number / VDIF) through the 10 GigE outputs.

The R2DBE components will be installed in the same rack-mounted 2U RDBE-G chassis modified to accommodate the ROACH2 and support components, Figure 6 and Figure 7. It supports two IFs, requiring two ADC samplers in the system and is presently undergoing verification, consisting of zero-baseline correlation with an RDBE-G. Operational R2DBE-G units are expected to be available by late 2017.

4 Mark 6 Developments

In 2016, an investigation of the internal temperatures of the Mark 6 host chassis was initiated and was conducted while data were recorded at a sustained 16 Gbps. The investigation was prompted by failures of the 10 G Ethernet NIC hardware at altitudes greater than 3,048 meters. The result of the study was a modification kit for the Mark 6 that reduced the internal temperature by using increased fan speeds, fan ducts, and an air flow deflector plate. A poster summarizing the study was presented at the IVTW at Haystack (http://www.haystack.mit.edu/workshop/ivtw2016/presentations/cruszczyk_poster_ivtw2016.pdf).

Lastly, Mark 6 software v1.3 was developed with added features and bug corrections. The corrections focused on strengthening the resiliency of the Mark 6 software. This software release is available at http://www.haystack.edu/tech/vlbi/mark6/software.html.

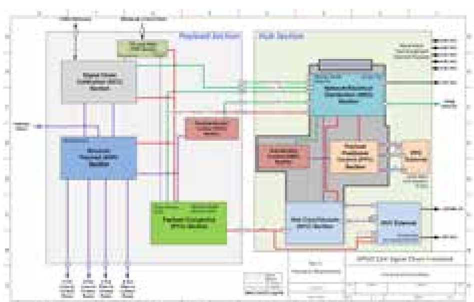

Fig. 1 Block diagram of the signal chain frontend sub-system.

Fig. 2 Signal Chain frontend deployed at KPGO (focus cone).

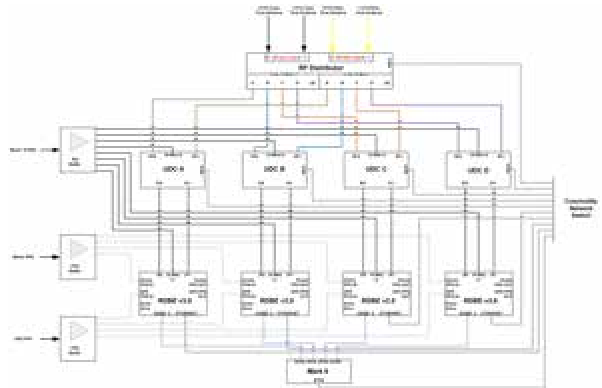

Fig. 3 Block diagram of the signal chain backend sub-system. External connections into the backend from the top represent those to the frontend sub-system. External connections into the frontend from the left/right represent those from the site's general infrastructure (not provided by Haystack).

Fig. 4 Signal Chain backend sub-system as deployed at KPGO control room.

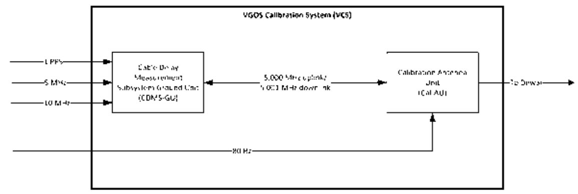

Fig. 5 Block diagram of the cable delay measurement system.

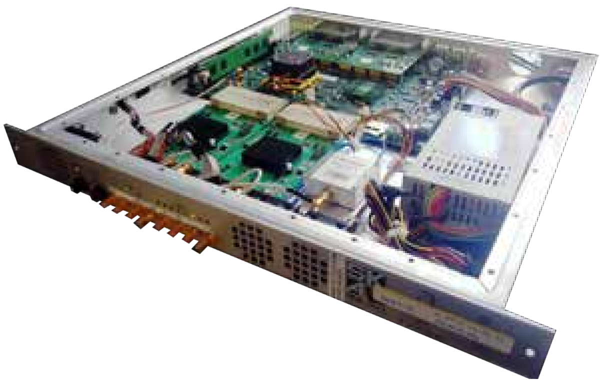

Fig. 6 Roach2 in EHT 1U chassis.

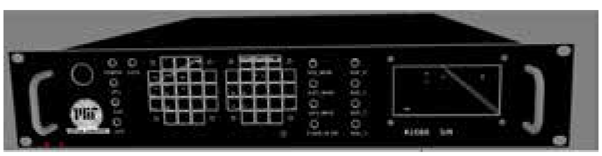

Fig. 7 R2DBE-G front panel.

Fig. 8 R2DBE-G back panel.

IAA Technology Development Center 2015—2016 Report

Dmitry Marshalov, Sergey Grenkov, Evgeny Nosov

Abstract The experience of operating the fast slewing, new radio telescope RT-13 showed that domestic VLBI observations for extreme characteristics are not enough. It is necessary to carry out regular observations as part of the international VLBI network, most of whose radio telescopes use only the narrowband backend system. To ensure compatibility, the RT-13 backend system was expanded to have the external digital converter bank (DDCB).

1 External Digital Downconverter Bank for BRAS

1.1 Introduction

Broadband Acquisition Systems (BRAS) have been used on new, fast slewing radio telescopes RT-13 of the "Quasar-KVO" complex from 2014 [1]. The system implements eight wideband channels of 512 MHz that allow the achievement of high sensitivity of the radio interferometer but complicate the processing of joint observations with narrowband types of backends which are still used on most existing VLBI radio telescopes. To simplify such observations, IAA RAS is developing an external digital downconverter bank (DDCB) [2]. The results of the development are presented.

Institute of Applied Astronomy of Russian Academy of Science

IAA RAS Technology Development Center

IVS 2015+2016 Biennial Report

1.2 System Structure

Three BRAS outputs are connected to the DDCB in parallel with the data transferring and recording system (DTRS) through the high-speed Cisco Nexus switch (Figure 1). Three channels are required to simultaneously receive data of two X-bands and one S-band from the BRAS outputs. This provides a regular geodetic observation mode with frequency synthesis in 270 MHz at S-band and 720 MHz at X-band respectively.

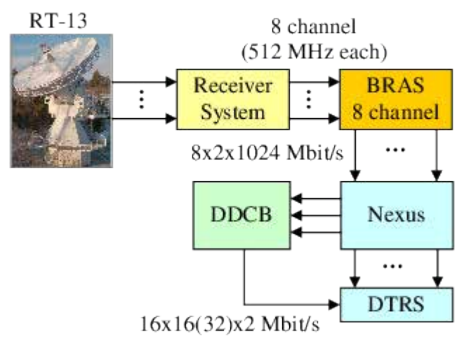

Fig. 1 The connecting structure for DDCB to RT-13.

The DDCB includes three optical receivers that provide the physical layer for transmitting and receiving the data flows through 10 Gbit/s Ethernet fiber-optic lines, a digital signal conversion module that is implemented in the field programmable logic gate array (FPGA), an Ethernet interface controller, and two local reference oscillators.

The FPGA performs the following operations: buffering data, transforming specified spectrum areas to video frequency, formation of output data, and containing 16 narrowband channels in VDIF format [3]. Output data from an FPGA GTX port through the optical transceiver SFP + are transmitted to the data buffer device by a 10 GE Interface.

The DDCB is controlled by a radio telescope central computer via 10/100/1000 Ethernet interfaces. A MicroBlaze processor for control is implemented in the FPGA configuration.

The digital converter module is realized on a KC705 development board from Xilinx (Figure 2) with an XC7325T FPGA. The digital converter module contains three independent data buffers, the three pre-filters based on a polyphase filter bank [4], a 16-channel switch, and 16 digital frequency converters. The processing of digital flows in each downconverter is divided into several stages: separation of the upper and lower sideband signal after a pre-filtration stage, moving a predetermined portion of the spectrum to lower frequencies, video bandwidth formation, and subsequent formation of two-bit data flow. In addition, the FPGA configuration contains a timer, a VDIF frame data pack unit, an Ethernet frame pack unit, a data capture module, and a MicroBlaze control processor.

Fig. 2 The DDCB with an open case.

The output formatter of the VDIF-frame integrates the data from downconverter outputs into one total flow, which is then broken up into packets of a given size. The frame headers include service information obtained by decoding the input data from BRAS, as well as additional DDCB parameters. These data observations, together with service information packed in raw Ethernet-packets with the possible addition of UDP and IP headers, is transmitted through the interface to the transceiver 10 GE receiver-transmitter and next to the data buffering device on the radio telescope.

1.3 The Software

The controller was made on the basis of the MicroBlaze processor, which, formed in the FPGA, is the main element of the DDCB management system. Upon receiving a request, obtained via Ethernet, the controller forms a response, which contains control information (e.g., a synchronization check, the presence of transceivers, and other information). The obtained data are used to control the system operation.

To communicate with a computer through a UDP FPGA, an Ethernet-controller PHY 88E1111 and GMII interface is used. Text commands of UDP-packets from the control computer are processed by the MicroBlaze processor, which was formed in the FPGA.

1.4 Conclusion

The main DDCB components were developed and debugged: data buffer, pre-filtering, sideband separator and digital down converter, and output signal quantizer. The final adjustment of the developed firmware is being carried out to optimize FPGA resource utilization. Laboratory tests of the DDCB are currently being performed, and the first test with real observations has to be scheduled to be performed until mid-2017.

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NICT Technology Development Center 2015+2016 Biennial Report

Kazuhiro Takefuji, Hideki Ujihara, Tetsuro Kondo

Abstract The National Institute of Information and Communications Technology (NICT) is developing and testing VLBI technologies and conducts observations with this new equipment. This report gives an overview of the Technology Development Center (TDC) at NICT and summarizes recent activities.

1 NICT as IVS-TDC and Staff Members

The National Institute of Information and Communications Technology (NICT) publishes the newsletter "IVS NICT-TDC News (former IVS CRL-TDC News)" at least once a year in order to inform about the development of VLBI related technology as an IVS Technology Development Center. The newsletter is available at the following URL `http://www2.nict.go.jp/sts/stmg/ivstdc/news-index.html`. Table 1 lists the staff members at NICT who are contributing to the Technology Development Center.

Table 1 Staff members of NICT TDC as of January 2017 (listed alphabetically).

HASEGAWA, Shingo	KAWAI, Eiji
KONDO, Tetsuro	KOYAMA, Yasuhiro
MIYAUCHI, Yuka	SEKIDO, Mamoru
TAKEFUJI, Kazuhiro	TSUTSUMI, Masanori
UJIHARA, Hideki	

2 General Information

We have not only been developing a broadband VLBI system called GALA-V, which has to meet the VGOS (VLBI Global Observing System) requirements, but also upgrading Cassegrain optics antennas such as our 34-m radio telescope and compact telescopes for the project of Time and Frequency transfer. The distinguishing features of GALA-V are that we apply a direct sampler called K6/GALAS and broadband feed horns called IGUANA and NINJA.

Until now, we have installed two compact antennas (MARBLE1 and MARBLE2) at the National Metrology Institute of Japan (NMIJ) in Tsukuba, Ibaraki and the NICT headquarters in Koganei, Tokyo for the purpose of time and frequency (T&F) comparison between NICT and NMIJ. Both NICT and NMIJ keep the national time standard UTC(NICT) and UTC(NMIJ). We observed several VLBI sessions with the broadband system for the time and frequency comparison. Moreover, broadband sessions with other institutes, GSI and Tasmania University, were observed in 2015 and 2016.

Kashima Space Technology Center, National Institute of Information and Communications Technology

NICT Technology Development Center

IVS 2015+2016 Biennial Report

3 Direct Sampler K6/GALAS

The specifications of the direct sampler K6/GALAS [1] are shown in Table 2 (see [1] for the evaluation). With deployment of the K6/GALAS, the front and backend systems have become quite simple. Firstly, an RF signal is divided into a lower 8-GHz range and an upper 8-GHz range, which will cover the whole frequency allocation of VGOS. Because the RF signal is directly digitized without analog frequency conversion, the phase differences between the output channels are fixed at the sampling stage. Thus, highly precise delays can be derived after broadband bandwidth synthesis.

Table 2 Specifications of the direct sampler K6/GALAS.

Frequency range	0.01 to 24 GHz
Number of analog inputs	2
Sampling rate	16384 or 12800 MHz
Quantization	3 bit
DBBC	1GHz bandwidth, 2 bit, 4 streams
10GbE protocol	VDIF / VTP/ UDP / IP

4 Development of Wideband Feeds

New wideband feeds developed at NICT were installed at the Kashima 34-m antenna and the MARBLE VLBI station at Koganei, Tokyo as shown in Figures 1 and 2. These feeds were named NINJA because of their beam widths' flexible designs. The beam widths are 17 degrees for the 34-m, from the center of the sub-reflector to the edge, and 26 degrees for the new optics of the MARBLE 2.4-m. MARBLE was upgraded to a 2.4-m dish with Cassegrain optics to improve its sensitivity.

The NINJA feed has a sensitivity from 3.2 to 14.4 GHz in frequency with newly developed OMT. The project GALA-V uses 3.2–4.8 GHz, 4.8–6.4 GHz, 9.6–11.2 GHz, and 12.8–14.4 GHz simultaneously for our time and frequency transfer project. Moreover, a simultaneous astronomical observation of 6.7 GHz and 12.2 GHz methanol maser and other wide-band applications are possible.

The measured modified system temperature (Tsys) and aperture efficiency for each antenna are shown in Figures 3 and 4.

5 Wideband Bandwidth Synthesis

An algorithm for wideband bandwidth synthesis (WBWS) exceeding a bandwidth of 10 GHz has been developed [3]. The estimation of the differential total electron content (TEC) in the ionosphere is also included in the algorithm. The new algorithm was implemented in our bandwidth synthesizing software package KOMB [2] and successfully applied to 24-hour wideband observations of the Kashima–Ishioka baseline (Figure 5). The baseline length of about 50 km is considered to be a bit too short to detect the differential TEC; however, we could detect it successfully.

6 Wideband Bandwidth VLBI

We observed a broadband VLBI session with the Ishioka station and the Hobart station in 2016. Figure 6 shows the cross-spectrum on the baseline of Ishioka and MARBLE2. The flat phase on the figure indicates that every bandwidth was corrected successfully by WBWS processing with four 1 GHz bandwidths (5.4, 6.5, 8.2, and 10.1 GHz). After WBWS processing, the delay error of the synthesized band was improved, 14 times better than that of the single band of 5.4 GHz.

The first trans-Pacific broadband VLBI (multiple 1 GHz bandwidths) observations were made with the Hobart 12-m antenna in Tasmania, Australia and with the Ishioka 13-m and Kashima 34-m antennas in Ibaraki, Japan on August 9, 2016. The main goal of the session was to get the first fringes and obtain an ionosphere effect in a broadband result. Figure 7 shows the WBWS result without TEC correction, and the quadratic curvature in the cross-spectrum phase shows the ionosphere effect. Under the condition that a baseline is a few hundreds of kilometers long, it is difficult to obtain a TEC effect; however, with the longer baseline shown, the TEC effect appears clearly.

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Fig. 1 NINJA feed (left) and IGUANA feed (right) in the feed cone of the Kashima 34-m antenna.

Fig. 2 Renewed MARBLE with 2.4-m dish and the NINJA feed.

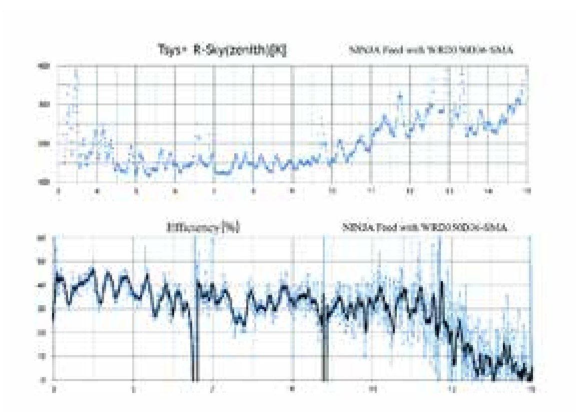

Fig. 3 Measurement of the modified system temperature and the aperture efficiency of the Kashima 34-m antenna with the NINJA feed.

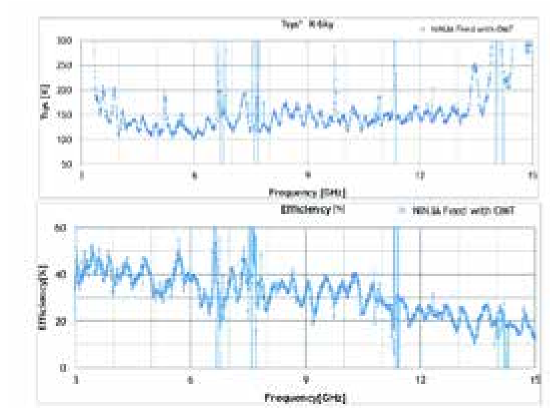

Fig. 4 Measurement of the modified system temperature and the aperture efficiency of the renewed MARBLE2 with the NINJA feed.

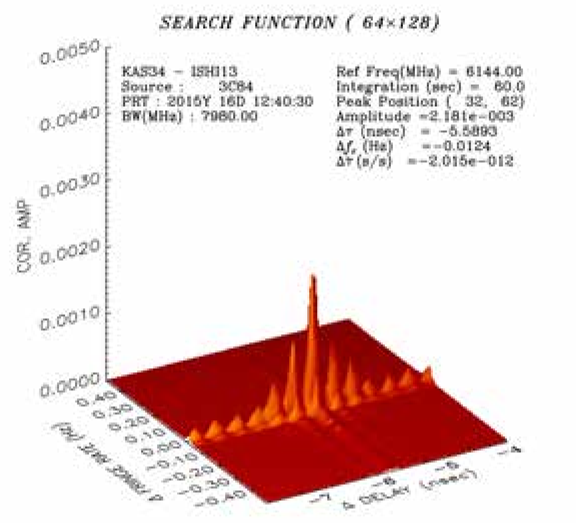

Fig. 5 An example of the fringe search function (source: 3C84, date: Jan.16, 2015).

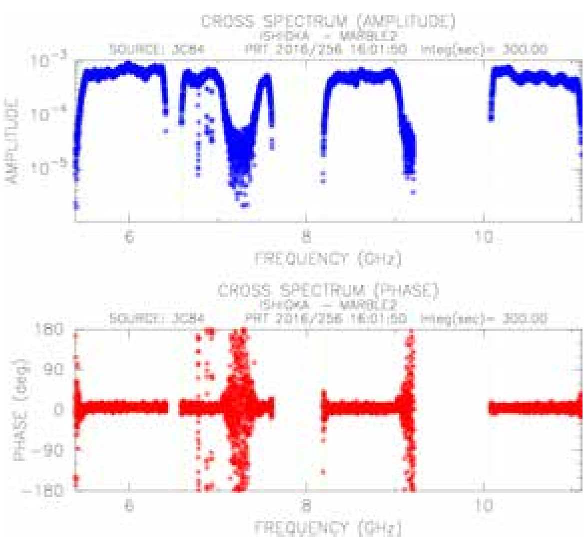

Fig. 6 Wide bandwidth synthesis was performed on the baseline between Ishioka and MARBLE2.

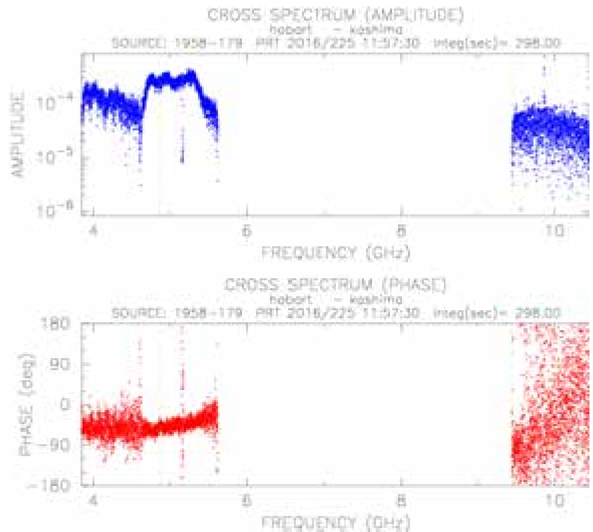

Fig. 7 The contribution of the ionosperic effect appears on the cross-spectrum of the Hobart12–Kashim34 baseline.

Onsala Space Observatory – IVS Technology Development Center Activities during 2015–2016

Miroslav Pantaleev, Rüdiger Haas, Bhushan Billade, Leif Helldner, Karl-Åke Johansson, Lars Petterson, Jonas Flygare, Ulf Kylenfall, Jens Dahlström, Magnus Dahlgren

Abstract We give a brief overview of the technical development related to geodetic VLBI done during 2015 and 2016 at the Onsala Space Observatory with emphasis on details of the design and tests of the signal chain for the Onsala Twin Telescopes project.

1 General Information

The technical development work for geodetic VLBI at the Onsala Space Observatory (OSO) was entirely dedicated to the Onsala Twin Telescopes (OTT) project. It included the design, assembly, testing, and installation of the OTT signal chain. The main activities can be summarized as follows and are discussed in more detail in the subsequent sections:

- construction of cryogenic receiver and selection of feeds.
- design and construction of the signal chain.
- time and frequency distribution system.

The telescopes were ordered in late 2014 from MT Mechatronics [1]. During 2015 the necessary infrastructure work was done at OSO to prepare for the installation of the telescopes. Two concrete towers were constructed to provide very stable long-term foundations for the telescopes. The towers are located 75 m apart from each other. The construction work was finished in early spring of 2016. The infrastructure work performed during 2015 and 2016 included also installation platforms, road work, electricity, and fiber and computer network.

Chalmers University of Technology, Department of Earth and Space Sciences, Onsala Space Observatory

OSO Technology Development Center

IVS 2015+2016 Biennial Report

Fig. 1 Photo of the OTT taken on 15 August 2016 during the lift of the azimuth cabin on to the concrete tower of the northern telescope. The two reflectors and the azimuth cabin of the southern telescope are still on the ground. The telescope towers have no cladding yet.

The telescopes were delivered to OSO in June 2016 and the assembly and installation was carried out during the summer and autumn of 2016. The photo presented in Figure 1 was taken during the lift of the azimuth cabin on top of the concrete tower of the northern telescope. The two reflectors and the azimuth cabin of the southern telescope are still on the ground. The telescopes are equipped with axis-symmetric ring focus, dual-reflector systems with primary and secondary reflectors of 13.2 m and 1.55 m in diameter, respectively. The site acceptance test for the OTT took place at the end of November 2016.

2 Construction of Cryogenic Receivers and Selection of Feeds

The cryogenic receivers integrate the broadband feeds and the first stage amplifiers at cryogenic temperatures to provide ultimate sensitivity. The receiver design was driven by two requirements: 1) to fit into the feed cone on the telescopes and 2) to make the interior and the volume dedicated for the feed installation flexible enough to accommodate different types of feeds. Figure 2 shows the two OTT cryostats during the assembly in the OSO Electronics Laboratory in August 2016. The feed selection was dictated by frequency range, sensitivity, and polarization properties.

After consultation with the IVS VGOS Technical Committee (VTC) and taking into consideration the local RFI situation at OSO as well as the requirements for keeping compatibility with the legacy S/X system, we decided to use two different feeds for the two OTT telescopes. One receiving system will be equipped with a 3–18 GHz Quad-Ridged Feed Horn (QRFH) [2] and the other with an Eleven Feed for the 2–14 GHz range [3]. The mechanical design of the vacuum window and the infrared window was done to make it suitable for both the Eleven feed and the QRFH. The two systems are exchangeable so that either of the telescopes can be equipped with the QRFH or Eleven-feed receiver system.

Fig. 2 The two cryostats for the OTT during the assembly in the OSO Electronics Laboratory.

Fig. 3 The interior of the two OTT cryogenic receivers with QRFH (left) and Eleven-Feed (right).

Special care in the cryostat design was taken in order to provide good mechanical references between the feed mechanical position and the interface to the telescope. This will ensure that the phase center of the feed will be well aligned with the focal point of the reflector system. For support of the receiver we used glass-fiber pipes with lateral openings to access the cryostat interior and mount components. The feed is mounted on a plate bolted to the glass-fiber support and connected with flexible copper braids to the cold head to transfer the heat and at the same time to prevent transfer of mechanical vibrations from the cold head to the feed. Pictures of the interior of the cryostats are shown in Figure 3. The first stage Low Noise Amplifiers (LNA) for the two receivers were purchased from Low Noise Factory [4]. The signals from the feed are fed first to directional couplers for inserting noise calibration signals and then passed to the LNAs.

The purchase of the QRFH was agreed with Sander Weinreb at Caltech Institute of Technology. A contractual agreement was set up between OSO and Caltech to scale up the existing 2–14 GHz Caltech QRFH design and to optimize the performance to provide optimal efficiency for 3–18 GHz for the MT Mechatronics ring focus reflector system. The optimization was carried out using CST Microwave studio [5]. The goal was to obtain 60% efficiency over 90% of the 3–18 GHz frequency range at a fixed focus position of the feed. Two feeds were purchased with the provision that the cryostat with the Eleven feed could be upgraded with QRFH at a later stage. The feeds were received in August 2016 and the beam patterns were measured in the beam measurement range at the Antenna Group, Department of Signals and Systems, Chalmers University of Technology. The aperture efficiency calculated from measured QRFH beam patterns is presented in Figure 4. It is below the expected 60% over large parts of the band. However, as it will be discussed later in this section, the sensitivity obtained from the measured equivalent noise temperature is nonetheless expected to be well within the VGOS specifications.

The integration of the QRFH was accomplished in November 2016 and the equivalent receiver noise was tested at the newly build Y-factor measurement facility at the OSO Electronics Laboratory using the sky as cold load and an absorber at ambient temperature as hot load. The results are presented in Figure 5. The careful design of the cryostat opening that does not truncate the beam, the efficient cooling of the feed, and especially the use of an amplifier with very low equivalent noise temperature made it possible to reach excellent receiver noise. The equivalent receiver noise is in the order of 10 K for approximately half of the receiver band. The increase in receiver noise at the low part of the band is due to a mismatch between the feed impedance and the input impedance of the LNA.

In order to accurately estimate the overall system sensitivity, the spillover noise contribution after the reflector system has to be estimated accurately. The estimation of the overall on-sky sensitivity of the QRFH was done using a GRASP system simulator [7], where the field patterns were analyzed in the reflector geometry using GRASP [6]. The sensitivity for a large range of telescope elevation angles was simulated with the system simulator using measured QRFH data and the receiver noise test results presented in Figure 5 to estimate the equivalent system noise. The simulated system sensitivity for the reflector looking at zenith is presented in Figure 6. The VGOS sensitivity specification is set in [8] as 2,000 Jy over all elevation angles. Our analysis showed that the sensitivity of the QRFH receiver is well below the specification for the whole range of elevation angles between ten degrees and zenith.

For the integration of the Eleven feed we decided to use a passive feeding network in front of the LNAs, thus decreasing the number of amplifiers from eight

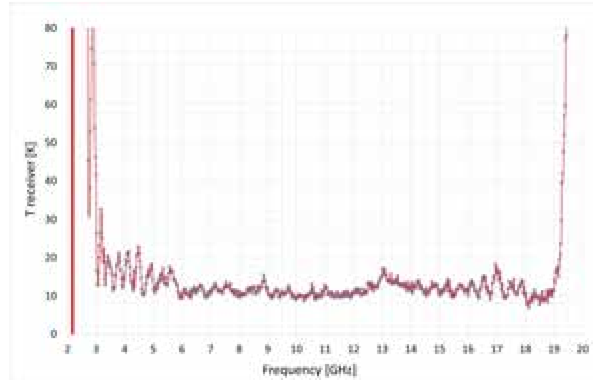

Fig. 5 Results from the Y-factor measurements of the QRFH receiver.

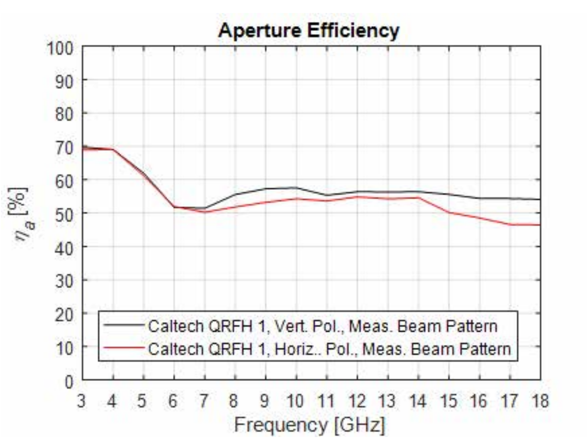

Fig. 4 Aperture efficiency of the 3–18 GHz Caltech QRFH calculated from measured beam patterns.

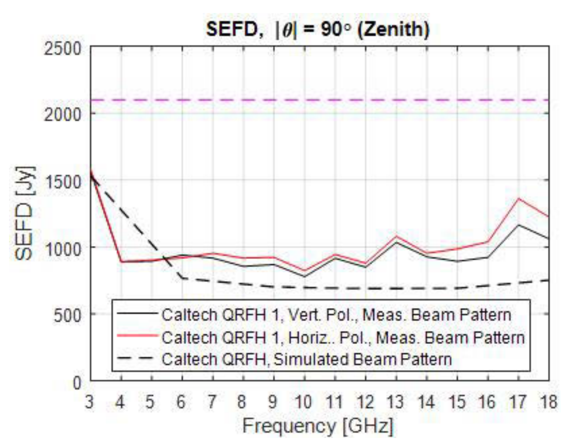

Fig. 6 Simulated SEFD using measured QRFH beam patterns and Y-factor test results.

(four LNAs per polarization) to two (one LNA per polarization). Tests were done in December 2015 and the measured equivalent receiver noise was in the order of 25 K. We did the same analysis as described in the previous paragraph to estimate the expected sensitivity and the results showed that this system will achieve SEFDs below 2,000 Jy.

3 Signal Chain

As the OTT telescopes are placed approximately 800 meters from the H-maser in the 20-m antenna building, we had to decide how to transfer frequency and RF signals, and where to locate the backends. Three possible placements for the backend systems were discussed: 1) in the towers of the telescopes, 2) in the 25-m control room, and 3) in the 20-m control room. After careful consideration of advantages and disadvantages for each of these alternatives we decided to place the backends of type DBBC3 [9] in the 20-m control room and to transfer the frequency from the existing H-maser in the 20-m building to the OTT. For the distribution of the RF as well as frequency we decided to use Radio Frequency over Fiber (RFoF) links. The installation of all fiber links was made taking into account very good thermal insulation. The fibers are placed at least 80 cm below surface, where possible, and insulated with thick foam everywhere else. The type of fiber cable used is LS Cable LSGS-06-OC0190-02 G.652D single mode fiber. This cable type was selected because of its excellent thermal coefficient of delay.

The term "Signal Chain", as used in this report, covers the entire active and passive RF circuitry used to amplify the astronomical signals received by the telescope, to couple noise and phase calibration into the system, to provide a link over optical fiber cable over a distance of almost one kilometer, and also to split the whole frequency band into sub-bands that are fed into the digital backend system. It consists of four functional units, interconnected in the following order: cryogenic receiver, RF front-end, RFoF link, and RF backend.

The functionality of the cryogenic receiver as part of the signal chain is to capture the signals from the telescope via the feed horn, couple phase and noise calibration, and provide low noise amplification. The RF front-end unit provides second stage amplification. To avoid potential problems with the dynamic range of the RFoF link as well as to mitigate possible saturation of the amplifiers in the signal chain due to strong RFI signals, we decided to split the RF-band at the output of the receiver into two sub-bands and use two RFoF links for the Low and High sub-bands of each polarization. This functionality is also provided from the RF front-end. The RFoF links were purchased from RF Optics [10]. In the control room the optical signals are down-converted to RF. At the output of the optical receivers for the Low and High sub-bands we installed filter banks to form four IF channels that are passed to the DBBC3. Several options for the filter banks were discussed. The goal was to design a system that will provide full VGOS operations in the future and at the same time be compatible with the present Haystack system to allow VLBI sessions as early as possible. At present time (end of 2016) Haystack is using 512-MHz bandwidth around center frequencies of 3.3, 5.5, 6.6, and 10.5 GHz. After discussions with Jim Lovell and Gino Tuccari [11] we adopted the IF bands as listed in Table 1.

Table 1 Filter bands for four channels fed to the digital backend.

Band	Bandwidth (−20 dB) [GHz]	Pass-band [GHz]	LO [GHz]	IF [GHz]
1	1.8– 4.1	2.0–3.8	–	2.0–3.8
2	3.7–7.7	3.8–7.6	7.7	0.1–3.9
3	7.5–11.5	7.6–11.4	7.5	0.1–3.9
4	11.3–15.3	11.4–15.2	11.3	0.1–3.9

4 Frequency Distribution

As described in the previous section we decided to distribute frequency over a RFoF link from the H-maser at the 20 m to the OTT. The complexity of finding the best technical solution was additionally complicated because of the selection of the strategy for integrating the Cable Delay Measurement System (CDMS). We considered two alternative solutions for transferring time and frequency: a) actively compensated link from Menlo Systems, model RFCD1500, and b) using Cable Delay Measurement System (CDMS) from MIT Haystack [12]. After some experiments and considering the project time line we decided for the CDMS with ground units and RFoF transmitters both installed at the H-maser in the control room of the 20 m and RFoF receiver and antenna units installed at the receiver in each of the telescopes. The distribution of the 5-MHz frequency uses WDM (wavelength division multiplexing) fiberoptical transceivers and a two-way fiber between the CDMS units.

5 Current Status and Future Plans

In December 2016, the receiver with QRFH was installed in the northern telescope. The photo shown in Figure 7 was taken in the elevation cabin with the receiver installed on the trolley that provides transportation to the operational position in the telescope's focal plane. The signal chain was verified by sweeping a continuous wave signal via the directional coupler in front of the LNA and monitoring the response on a spectrum analyzer in the 20-m control room.

The plan for 2017 is to bring the OTT into full network operation and to participate in the CONT17 session in the autumn of 2017. During the spring of 2017 we will proceed with the scientific commissioning of the OTT infrastructure. The first step will be to perform comprehensive tests of the receiver and signal chain doing SEFD measurements, pointing, beam maps, and optimizing of the illumination of the subreflector. The next step will be to verify the performance of the CDMS checking long-term stability when the telescopes are in motion over a wide range of day and night temperature variations. The third step of the scientific commissioning is bringing into operation the two DBBC3 units that will be delivered in February.

We also plan to establish a new GNSS reference installation in the vicinity of the OTT. The antenna will be mounted on a slightly higher location (the site and antenna cable are already prepared) and the ground below should be covered with electromagnetic absorber material in order to minimize multi-path reflections. Furthermore, we plan to establish a network for local survey and monitoring of the OTT.

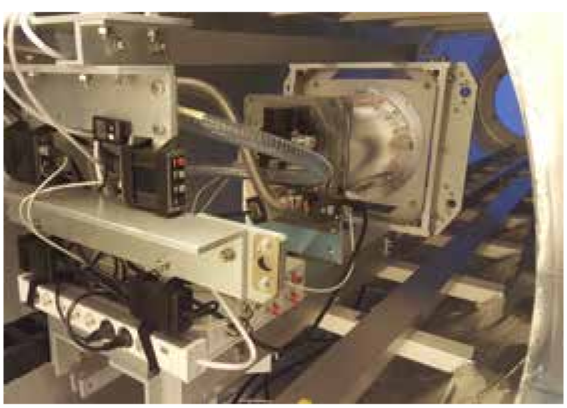

Fig. 7 Receiver with QRFH installed in the northern telescope.

Acknowledgements

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IGN Yebes Technology Development Center

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Abstract The activities in technical development related to geodetic VLBI done during 2015 and 2016 at IGN Yebes Observatory were focused on different topics that are detailed below.

1 RAEGE Radio Telescopes

The RAEGE radio telescope at Yebes Observatory (Spain) is currently equipped with a VGOS-compliant broadband receiver. The broadband receiver, which was developed and tested in the laboratory during 2015, was installed on February 24, 2016.

The first fringe detection with the broadband receiver in the Yebes VGOS radio telescope was confirmed on April 28, 2016. Some more tests were performed during May and June. After this, it participated in seven VGOS sessions. The first observation using four sub-bands and four RDBEs was performed on December 19, 2016.

Regarding RAEGE station on Santa María island (Açores, Portugal), it is currently equipped with a tri-band receiver (S/X/Ka). The tri-band receiver was installed on November 7, 2016, after being developed during 2015 and 2016. Onsite works continued during 2015 and 2016, and the first light was delayed to the first half of 2017.

With respect to the next RAEGE radio telescope on the Canary Islands, its mechanical parts arrived on Gran Canaria island in 2016, where RFI tests are being performed to find a suitable location. Once the site is identified, civil works and assembly can start.

Finally, it has to be mentioned that the invariant points of the Yebes 40-m and 13.2-m telescopes were measured, as reported in [1].

2 VGOS Broadband Receiver

The cryogenic front-end of the broadband receiver consists of a Dewar with a dual-linear polarization quadruple-ridged flared horn (QRFH), directional couplers for calibration signal injection, and two ultra-low noise hybrid amplifiers, one for each polarization. The refrigerator is based on the Helium Gifford-McMahon closed-cycle approach, which cools the components down to 10 K.

The block diagram of the receiver is shown in Figure 1. The output signals from the Dewar are sent via RF-over-fiber optic links to the backend room, where they are distributed to four dual-channel frequency up/down converters. Each converter allows selection of a frequency sub-band in both polarizations, with 1.5-GHz bandwidth[1], in the range 2–14 GHz, and its conversion to baseband (DC – 1.5 GHz).

The converter design and construction has been accomplished and implemented by the engineers and technicians of the receiver group at Yebes Observatory, using the Haystack design as a starting point.

Figure 2 shows an internal view of the front-end, which was introduced in [2].

The noise temperature of the complete receiver was measured, and Tcal was calibrated. The results of the

[1] The final bandwidth, either 500 MHz or 1 GHz, is selected in the backend.

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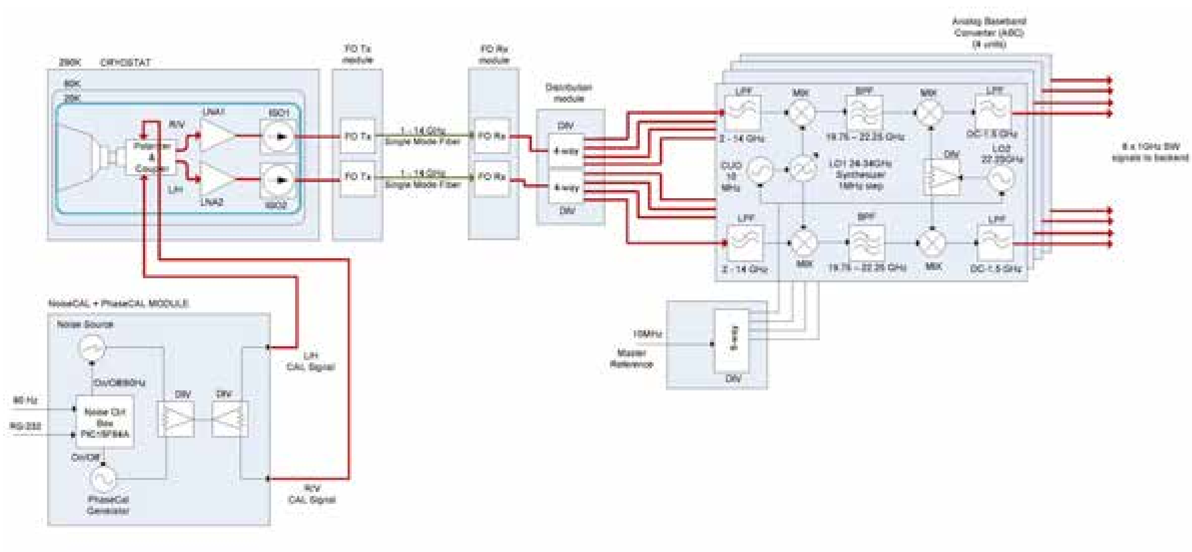

Fig. 1 Broadband receiver block diagram.

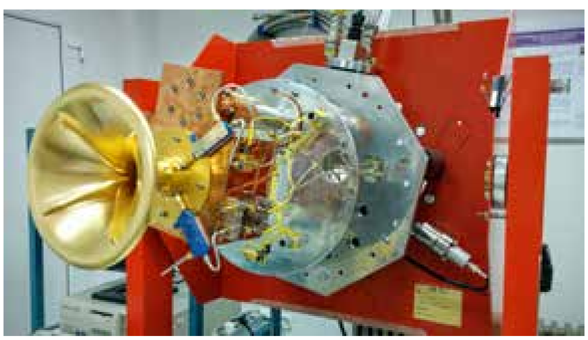

Fig. 2 Broadband receiver internal view.

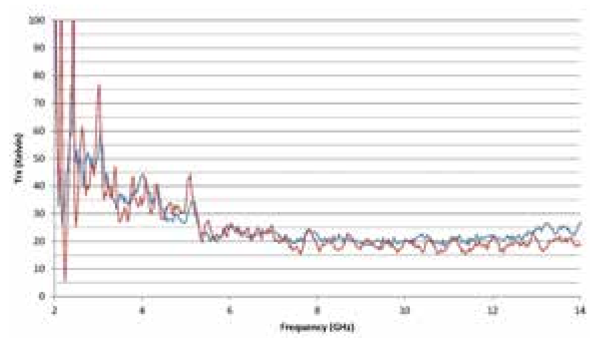

Fig. 3 Broadband receiver noise temperature.

receiver noise measurements are shown in Figure 3. The blue trace shows the result for one polarization with a balanced low-noise amplifier configuration, while the red one corresponds to the other polarization with a single low-noise amplifier. The matching of the balanced configuration is much better. As a result, the ripple across the band is lower than in the channel with a single amplifier. The measured receiver noise temperatures are lower than 25 K for most of the band. However, the existence of RFI signals in S and C bands, due to WiFi, UMTS, Bluetooth, and WiMax, among others, provides anomalous values for the low frequency range.

Finally, a digital phasecal generator was developed, using the Haystack design as a starting point.

3 Tri-band (S/X/Ka) Receiver for Santa María Station

A second cryogenically cooled tri-band receiver has been successfully developed [3, 4, 5]. At this time, three of these receivers have been built: two of them for the RAEGE radio telescopes, in Yebes and Santa María, and one for GSI's Ishioka station in Japan. The tri-band receiver allows simultaneous dual-circular polarization observations at S (2.2–2.7 GHz), X (7.5–9 GHz), and Ka (28–33 GHz) bands. It can be used in legacy S/X mode, in X/Ka mode, and, in addition, at Ka-band, allowing accurate measurements of pointing, tracking, and antenna efficiency during the commissioning phase.

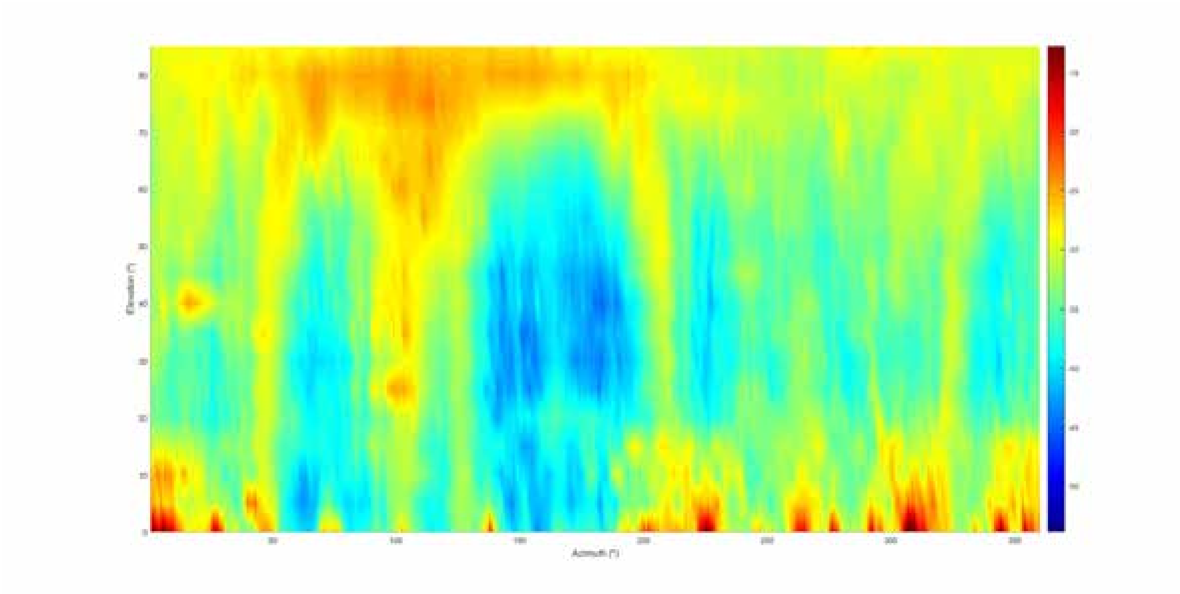

Fig. 4 Elevation over azimuth map of RFI power.

The receiver noise temperatures are lower than 25, 35, and 35 K, respectively. The receiver is fully integrated into a frame box positioner that facilitates the installation at the radio telescope feed cone, together with the downconverters, tri-band noisecal and phasecal, LNA biasing modules, and cryogenics and vacuum monitoring equipment.

The current receiver will be replaced by a new VGOS broadband receiver by 2018.

4 RFI Measurements

First tests of the VGOS broadband receiver, after installation in the 13.2-m radio telescope, showed saturation issues due to RFI signals in the lower part of the band [6]. The initial room temperature amplifiers, in front of the fiber optic link, were under saturation, and, in addition, they were saturating the fiber optic link, too. These amplifiers had to be removed. However, an increase of the system noise temperature was detected, due to the high noise figure value of the fiber optic link.

The RFI power at the output of the Dewar was measured with a total power detector up to 6 GHz, where the RFI signals are more powerful. The radio telescope was driven to acquire an elevation-over-azimuth map which is shown in Figure 4 for the vertical polarization. It can be seen that, at elevation angles under 10 degrees, approximately, the power at the output of the Dewar can be as high as -15 dBm.

Spectral measurements were performed as well, showing that the most relevant RFI comes fron GSM, UMTS, fixed service radio-links, WiFi, Bluetooth, and WiMax [7]. Several other tests were performed with different filters at the output of the Dewar, showing better performance. As a result, a custom filter is going to be installed to solve this issue.

5 LNA Development

During the reporting period, several cryogenic S and X band amplifiers of receivers from Wettzell and AGGO (former TIGO) were inspected and repaired (when needed) using Yebes dedicated laboratory cryostats. New cryogenic amplifiers for the Santa María tri-band receiver, based on the same design used in Yebes, were produced and delivered.

Regarding new developments, the activity with the 2–14 GHz wide-band cryogenic amplifiers for VGOS stations has continued. The 2014 report presented the results obtained with a Yebes design built using US InP NGST HEMT devices. The performance was excellent, but the experimental InP devices used are subject to se-

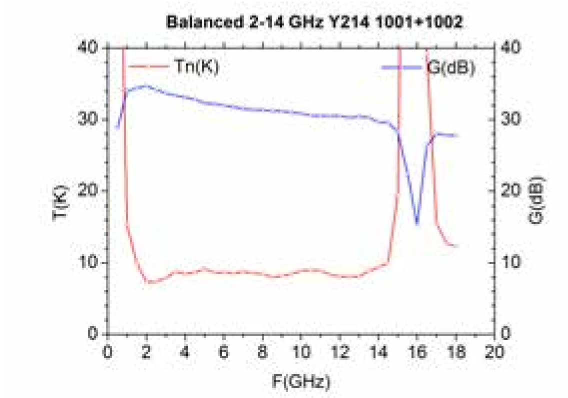

Fig. 5 Gain and noise temperature of a balanced 2–14 GHz cryogenic amplifier as measured in a test cryostat.

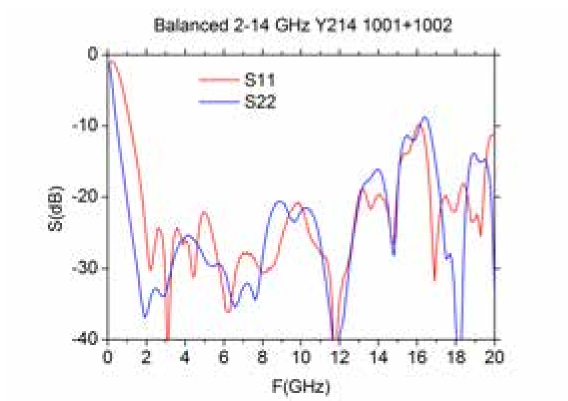

Fig. 6 Input and output matching of a balanced 2–14 GHz cryogenic amplifier as measured in a test cryostat.

vere ITAR regulations and could not be exported freely. During the reporting period it has been possible to obtain the same level of performance using European InP devices developed by ETH Zurich, Switzerland. This opens the door for providing this design to other IVS stations with the need for hard to procure, reliable, and state-of-the-art wideband cryogenic amplifiers.

One of the problems of wideband 2–14 GHz receivers is the poor match (high reflection coefficient) of the feeds and the amplifiers in the low frequency region, which causes ripples in noise and gain. To avoid this problem, a balanced configuration using two amplifiers and specially developed 90° cryogenic hybrid couplers has been designed, produced, and tested. The input and output reflection is drastically improved to the level of -20 dB in most of the band, with a slight penalty in noise w.r.t. a single-ended unit (see Figures 5 and 6). The peak in Figure 5 around 16 GHz is due to the 90° cryogenic hybrid. Another application of the 90° hybrid could be to obtain circular polarization from the combination of the two linear polarization outputs of the feeds.

A new prototype of the Ka-band amplifier has been built using novel InAs HEMT devices developed at ETH. This exotic semiconductor has the potential of obtaining even lower noise and power dissipation at cryogenic temperatures than InP. A noise temperature of less than 10 K was measured in the 32–35 GHz VLBI band.

The existence of reliable sources willing to produce adequate HEMT devices for the cryogenic low noise amplifiers needed in radio astronomy is of maximum importance for maintaining the competitiveness of our instruments. In this respect, Yebes has been involved in cooperation agreements with some European institutions (foundries) such as IAF (Germany) or ETH (Switzerland), allocating significant funding and resources within our limited possibilities. Perhaps a more dedicated effort with additional funding from other institutions would be needed to keep this technology alive and evolving in the future.

6 Software Developments

The installation of the broadband receiver required the development of software code to monitor and control its frequency and attenuation, the noise diode, and the phase cal system. The integration in the antenna control system and the data acquisition in single-dish mode was also developed and tested. The aperture efficiency of the system was measured in different bands between 3.5 and 14 GHz, and it ranges between 60% at lower frequencies to 40% at the higher end. The SEFD also ranges between 2000–5000 Jy along the frequency band. The results are summarized in [8].

The control system for the VGOS twin telescopes at Ny-Ålesund has been designed and developed, based on the Yebes 13.2 m one. The design allows both telescopes to be controlled independently or linked together. The software to monitor the Vaisala weather station, equipped with several sensors, a continuum detector for single dish observations, and a counter for measuring the cable delay, was developed too. All of this software together with the underlying infrastructure was installed at Yebes on the computers sent from the Norwegian Mapping Authority (NMA). A description of the works peformed is available in [9].

Onsala Space Observatory (OSO) asked Yebes Observatory for a report on the tests performed at the VGOS Yebes antenna to use it as a guide for testing their recently built VGOS twin telescopes at Onsala. Tests performed to check the servosystem and the control system developed at the Yebes VGOS telescope are described in [10].

7 Other Activities

Yebes Observatory has been in charge of refurbishing three S/X receivers from the German *Bundesamt für Kartographie und Geodäsie* (BKG) under a collaboration agreement. Receivers belong to the Wettzell, O'Higgins, and AGGO stations. For the latter, Yebes offered support for both the installation and commissioning on site. Vacuum, cryogenic, and RF performances have been improved by either the repair or replacement of some parts (e.g., cold heads, sensors, LNAs, and thermal transitions). Examples of these works can be found in [11, 12, 13].

In 2016 Yebes observatory supported our colleagues in Ny-Ålesund (Svalbard, Norway) during the site acceptance test (SAT) of their twin radio telescopes. This collaboration will be extended to support the installation of a tri-band receiver (S/X/Ka) to characterize and carry out their commissioning during 2017.

Yebes Observatory will also participate as a partner in the EU financed project H2020 RADIONET4 grant agreement 730562, for the development of a broadband VLBI receiver from 1.5 GHz to 15.5 GHz (WP BRAND-EVN), with a strong connection to VGOS [14].

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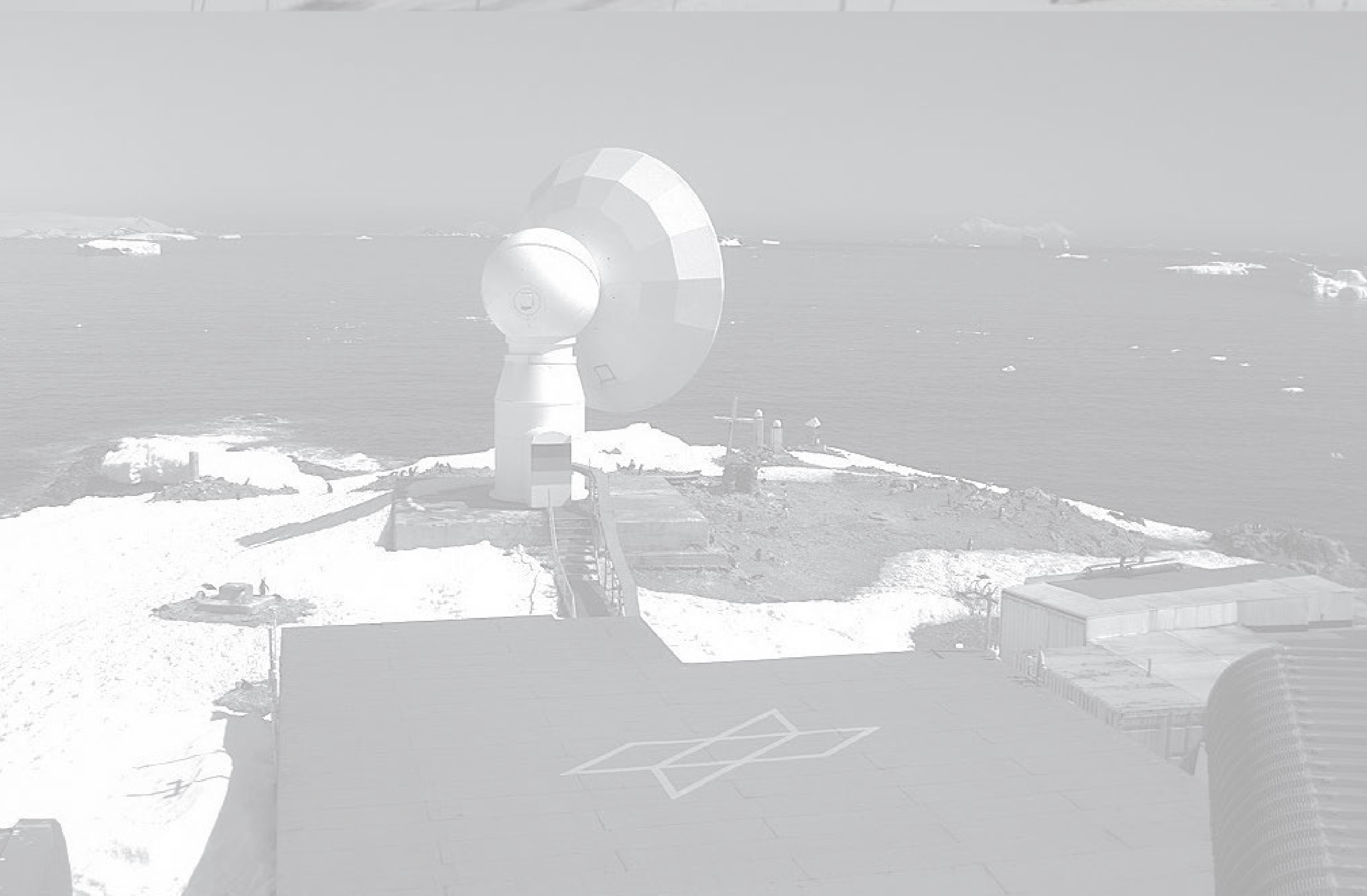

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1 Introduction

The following bibliography compiles papers that were published in the field of geodetic and astrometric VLBI during 2015 and 2016. There is no distinction between peer-reviewed, reviewed, or proceedings publications. This list is by no means exhaustive.

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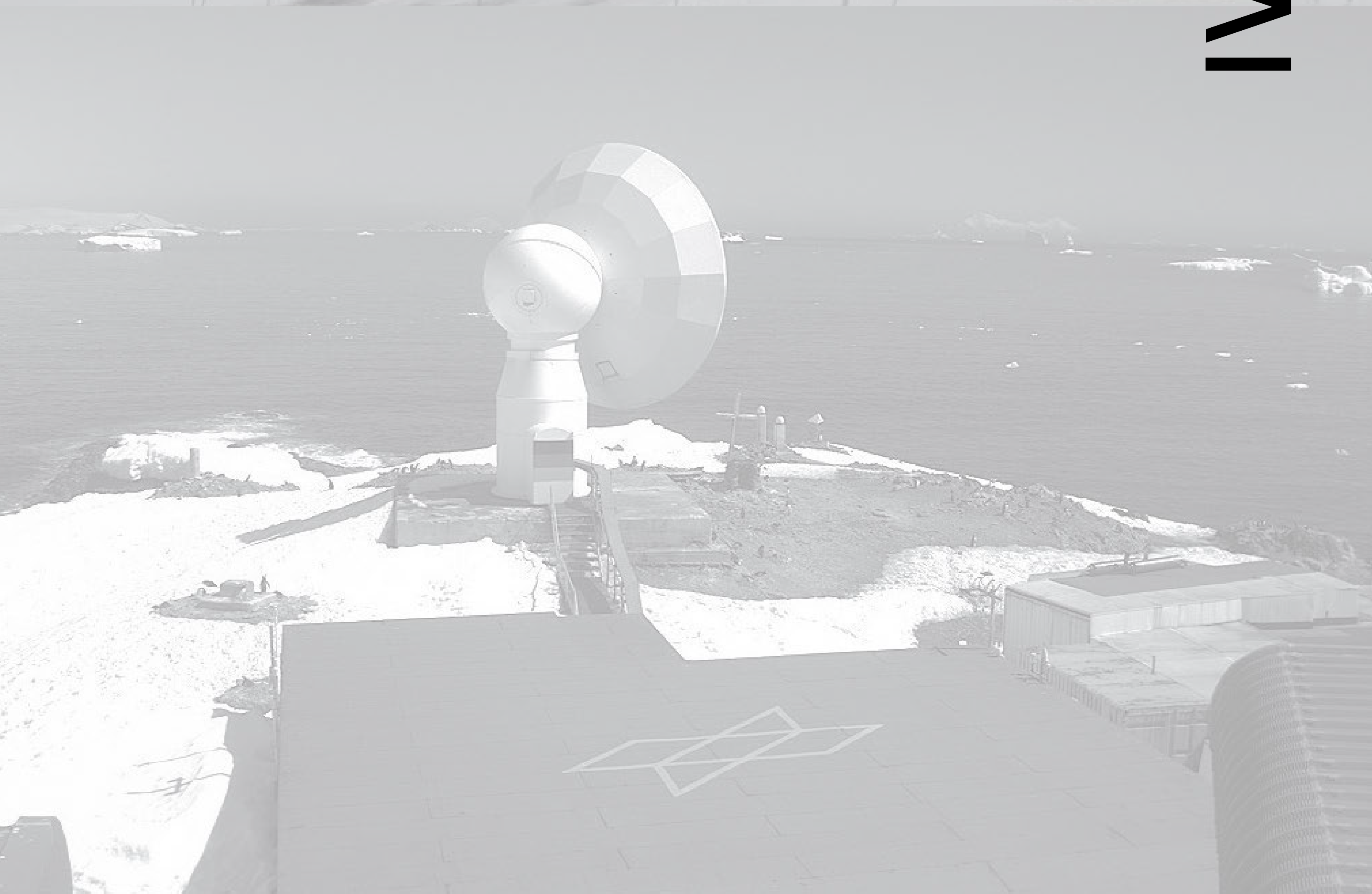
IVS Information



IVS Terms of Reference

1 Summary

1.1 Charter

The International VLBI Service for Geodesy and Astrometry (IVS) is an international collaboration of organizations which operate or support Very Long Baseline Interferometry (VLBI) components. IVS provides a service which supports geodetic and astrometric work on reference systems, Earth science research, and operational activities. IVS is a Service of the International Association of Geodesy (IAG) and of the International Astronomical Union (IAU).

1.2 Objectives

IVS fulfills its charter through the following objectives:

1. foster and carry out VLBI programs. This is accomplished through close coordination of the participating organizations to provide high-quality VLBI data and products.
2. promote research and development activities in all aspects of the geodetic and astrometric VLBI technique.
3. advance the education and training of VLBI participants through workshops, reports, and other means.
4. support the integration of new components into IVS.
5. interact with the community of users of VLBI products. IVS represents VLBI in the Global Geodetic Observing System (GGOS) of the IAG and interacts closely with the International Earth Rotation and Reference Systems Service (IERS).

In support of these objectives, IVS coordinates VLBI observing programs, sets performance standards for VLBI stations, establishes conventions for VLBI data formats and data products, issues recommendations for VLBI data analysis software, sets standards for VLBI analysis documentation, and institutes appropriate VLBI product delivery methods to ensure suitable product quality and timeliness. IVS coordinates its activities with the astronomical community because of the dual use of many VLBI facilities and technologies for both astronomy and astrometry/geodesy.

1.3 Data Products

VLBI data products contribute uniquely to these important activities:

- defining and maintaining the celestial reference frame,
- monitoring universal time (UT1), and
- monitoring the coordinates of the celestial pole (nutation and precession).

These results are the foundation of many scientific and practical applications requiring the use of an accurate quasi-inertial reference frame, such as high-precision positioning, navigation, and timing. In addition IVS provides a variety of VLBI products with differing applications, timeliness, detail, and temporal resolution, such as:

- all components of Earth orientation parameters,
- terrestrial reference frame,
- baseline lengths, and
- tropospheric parameters.

All VLBI data and products are publicly available in appropriate formats from IVS Data Centers.

1.4 Research

The IVS data and products are used for research in many areas of geodesy, geophysics, and astronomy, such as:

- UT1 and polar motion excitation over periods of hours to decades,
- solid Earth interior research (e.g., mantle rheology, anelasticity, libration, and core modes),
- characterization of celestial reference frame sources and improvements to the frame,
- tidal variations (solid Earth, oceanic, and atmospheric),
- improvements in the terrestrial reference frame, especially in the scale,
- climate studies (e.g., sea level change, deglaciation, and water vapor),
- regional and global geodynamics, and
- general relativity.

To support these activities, there are ongoing research efforts to improve and extend the VLBI technique in areas such as:

- instrumentation, data acquisition, and correlation,
- data analysis techniques,
- spacecraft tracking and navigation (Earth-orbiting and interplanetary), and
- combination of VLBI data and results with other techniques.

2 Permanent Components

IVS acquires, correlates, and analyzes VLBI data to produce geodetic, astrometric, and other results that are archived and publicized. IVS accomplishes its objectives through the following permanent components:

- Network Stations,
- Operation Centers,
- Correlators,
- Analysis Centers,
- Data Centers,
- Technology Development Centers, and
- Coordinating Center.

2.1 Network Stations

The IVS observing network consists of high performance VLBI stations.

- Stations may either be dedicated to geodesy or have multiple uses (including astronomical observations or satellite tracking applications).
- Stations comply with performance standards for data quality and operational reliability specified by the Directing Board.
- Stations provide local tie information, timing and meteorological data to the IVS Data Centers.
- VLBI data acquisition sessions are conducted by groups of Network Stations that may be distributed either globally or over a geographical region.

2.2 Operation Centers

The IVS Operation Centers coordinate the routine operations of specific networks. Operation Center activities include:

- planning network observing programs,
- supporting the network stations in improving their performance,
- generating the detailed observing schedules for use in data acquisition sessions by IVS Network Stations, and
- posting the observing schedule to an IVS Data Center for distribution and archiving.

IVS Operation Centers follow guidelines from the Coordinating Center for timeliness and schedule file formats.

2.3 Correlators

The IVS Correlators process raw VLBI data. Their other tasks are to:

- provide timely feedback to the Network Stations about data quality,
- jointly maintain the geodetic/astrometric community's media pool and transport,
- manage electronic data transfer,
- make processed data available to the Data Centers, and
- regularly compare processing techniques, models, and outputs to ensure that data from different Correlators are identical.

2.4 Analysis Centers

The IVS coordinates VLBI data analysis to provide high-quality products for its users. The analyses are performed by:

- Operational Analysis Center,
- Associate Analysis Centers,
- Special Analysis Centers for Specific Observing Sessions, and
- Combination Centers.

All Analysis Centers maintain and/or develop appropriate VLBI analysis software.

Operational Analysis Centers are committed to producing results to the specifications of the IVS Analysis Coordinator and always on schedule to meet IVS requirements. In addition, Operational Analysis Centers may produce Earth orientation parameters, station coordinates, and source positions in regular intervals.

Operational Analysis Centers place their final results in IVS Data Centers for dissemination to researchers and other users. They adhere to IVS recommendations for the creation of high-quality products and their timely archiving and distribution. Any deviations that an Operational Analysis Center makes from IVS recommendations are properly documented. Operational Analysis Centers provide timely feedback about station performance. In addition to these regular services, Operational Analysis Centers may also perform any task of an Associate Analysis Center.

Associate Analysis Centers are committed to regularly submit specialized products using complete series or subsets of VLBI observing sessions. The analysis is performed for specific purposes as recognized by the Directing Board, such as exploitation of VLBI data for new types of results, investigations of regional phenomena, reference frame maintenance, or special determinations of Earth orientation parameters. The Associate Analysis Centers place their final results in IVS Data Centers for dissemination to researchers and other users. They adhere to IVS recommendations for the creation of high-quality products and their timely archiving and distribution. Any deviations that an Associate Analysis Center makes from IVS recommendations are properly documented.

Special Analysis Centers for Specific Observing Sessions have responsibility for ongoing series-related investigations of one or more existing session types. They perform detailed and comparative analyses of each session of a series within a reasonable time after correlation. In addition, they report deficits and technical complications to the observing sites, the correlators, and to the schedulers as well as to the IVS Network and Analysis Coordinators.

Combination Centers are committed to produce combination results from the individual submissions of the Operational Analysis Centers as official IVS products. For this purpose they monitor the quality of the submissions. The official IVS products include, but are not limited to, EOP time series derived from session-based results for 24-hour network sessions and one-hour Intensive sessions. Combination Centers also contribute to the generation of the official IVS input to International Terrestrial Reference Frame (ITRF) computations. The combination work is done in a timely fashion and in close cooperation with the IVS Analysis Coordinator.

2.5 Data Centers

The IVS Data Centers are repositories for VLBI observing schedules, station log files, data and products. Data Centers may mirror other Data Centers to make the distribution and maintenance of data more efficient and reliable.

- Data Centers are the primary means of distributing VLBI products to users.

- Data Centers work closely with the Coordinating Center and with the Analysis Centers to ensure that all the information and data required by IVS components are quickly and reliably available.

  Data Centers provide the following functions:

- receive and archive schedule files from Operation Centers,
- receive and archive log files and ancillary data files from the Network Stations,
- receive and archive data products from the Analysis Centers, and
- provide access and public availability to IVS data products for all users.

2.6 Technology Development Centers

The IVS Technology Development Centers contribute to the development of new VLBI technology for improvement of the VLBI technique. They:

- investigate new equipment and approaches,
- develop, test, and document new hardware, firmware, and software for operations,
- assist with deployment, installation, and training for any new approved technology, and
- maintain and support operational equipment.

2.7 Coordinating Center

The IVS Coordinating Center is responsible for coordination of both the day-to-day and the long-term activities of IVS, consistent with the directives and policies established by the Directing Board. Specifically, the Coordinating Center monitors, coordinates, and supports the activities of the Network Stations, Operation Centers, Correlators, Data Centers, Analysis Centers, and Technology Development Centers. The Coordinating Center works closely with the Technology Coordinator, the Network Coordinator, and the Analysis Coordinator to coordinate IVS activities.

The primary functions of the Coordinating Center are to:

- coordinate observing programs approved by the Directing Board,
- create and maintain the master schedule of observing sessions in coordination with IVS Network Stations and astronomical observing programs,
- foster communications among all components of the IVS,
- coordinate the best use of community resources,
- develop standard procedures for IVS components,
- organize training in VLBI techniques,
- organize workshops and meetings, including IVS technical meetings,
- produce and publish reports of activities of IVS components,
- maintain the IVS information system and archive all documents, standards, specifications, manuals, reports, and publications,
- coordinate IVS outreach and educational activities,
- provide liaison with the IAU, IAG, GGOS, IERS, and other organizations, and
- provide the Secretariat of the Directing Board.

2.8 Becoming a Permanent Component

IVS will accept proposals at any time to become a permanent component. Such proposals will be reviewed for approval by the Directing Board.

3 Coordinators

Specific IVS activities regarding network data quality, products, and technology are accomplished through the functions performed by three coordinators: a Network Coordinator, an Analysis Coordinator, and a Technology Coordinator.

3.1 Network Coordinator

The IVS Network Coordinator is selected by the Directing Board from responses to an open solicitation to all IVS components. The Network Coordinator represents the IVS Network Stations on the Directing Board and works closely with the Coordinating Center. The Network Coordinator is responsible for stimulating the maintenance of a high quality level in the station operation and data delivery. The Network Coordinator performs the following functions:

- monitors adherence to standards in the network operation,
- participates in the quality control of the data acquisition performance of the network stations,
- tracks data quality and data flow problems and suggests actions to improve the level of performance, and
- coordinates software development for station control and monitoring.

The Network Coordinator works closely with the geodetic and astronomical communities who are using the same network stations for observations. The Network Coordinator takes a leading role in ensuring the visibility and representation of the network stations.

3.2 Analysis Coordinator

The IVS Analysis Coordinator is selected by the Directing Board from responses to an open solicitation to the IVS Analysis Centers. The Analysis Coordinator is responsible for coordinating the analysis activities of IVS and for stimulating VLBI product development and delivery. The Analysis Coordinator performs the following functions:

- fosters comparisons of results from different VLBI analysis software packages and different analysis strategies,
- encourages documentation of analysis and combination software,
- participates in comparisons of results from different space geodetic techniques,
- monitors Analysis Centers' products for high quality results and for adherence to IVS standards and IERS Conventions,
- ensures that IVS analysis and combination products from all Analysis Centers are archived and are available to the scientific community, and
- supervises the formation of the official IVS products specified by the IVS Directing Board.

The Analysis Coordinator plays a leadership role in the development of methods for generation and distribution of VLBI products so that the products reach the users in a timely manner. The Analysis Coordinator interacts with GGOS and the IERS and promotes the use of VLBI products by the broader scientific community. The Analysis Coordinator works closely with the astronomical communities who are using some of the same analysis methods and software.

3.3 Technology Coordinator

The IVS Technology Coordinator is selected by the Directing Board from responses to an open solicitation to the IVS Technology Development Centers. The Technology Coordinator performs the following functions:

- stimulates advancement of the VLBI technique,
- maintains awareness of all current VLBI technologies and ongoing development,
- coordinates development of new technology among all IVS Technology Development Centers,
- encourages technical compatibility with the astronomical community,
- encourages and oversees development of VLBI-related technical standards,
- coordinates the distribution of and access to technical documents and standards, and
- helps promulgate new technologies to the IVS community.

The Technology Coordinator works closely with the astronomical community, both to maintain technical compatibility between the geodetic and astronomical communities and to take advantage of technology development activities in the astronomical community.

4 Directing Board

4.1 Roles and Responsibilities

The Directing Board sets objectives, determines policies, adopts standards, and sets the scientific and operational goals for IVS. The Directing Board exercises general oversight of the activities of IVS including modifications to the organization that are deemed appropriate and necessary to maintain efficiency and reliability. The Directing Board may determine appropriate actions to ensure the quality of the IVS products.

The Directing Board will receive and review proposals for non-IVS research programs that request IVS resources.

4.2 Membership

The Directing Board consists of representatives of the IVS components, members at-large, appointed members, and ex officio members. The members are:

Representatives of IVS Components (see below):

- Correlators and Operation Centers representative (1)
- Analysis and Data Centers representatives (2)
- Networks representatives (2)
- Technology Development Centers representative (1)

Elected by the Directing Board upon recommendation from the Coordinating Center (see below):

- Members at large (3)

Selected by Directing Board upon review of proposals from IVS Member Organizations:

- Coordinating Center Director
- Network Coordinator
- Analysis Coordinator
- Technology Coordinator

Appointed members:

- IAU representative
- IAG representative
- IERS representative

Through a reciprocity agreement between IVS and IERS, the IVS serves as the VLBI Technique Center for IERS, and as such its designated representative(s) serve on the IERS Directing Board. In turn, the IERS Directing Board designates a representative to the IVS Directing Board. This arrangement is to assure full cooperation between the two services.

Total number: 16

The members appointed by IAU, IAG, and IERS are not subject to institutional restrictions.

The six members who are the representatives of the IVS components are elected by the IVS Associate Members. All elected members serve staggered four-year terms once renewable.

At-large members are intended to ensure representation on the Directing Board of each of the components of IVS and to balance representation from as many countries and institutions and IVS interests as possible. At-large members serve two-year terms once renewable.

A Directing Board member who departs before the end of his/her term is replaced by a person selected by the Directing Board. The new member will serve until the next official elections. The position will then be filled for a full term.

An individual can only serve two consecutive full terms on the Board in any of the representative and at-large positions. Partial terms are not counted to this limit. After serving two consecutive full terms, an individual becomes eligible again for a position on the Board following a two-year absence.

The three Coordinators are selected by the Directing Board on the basis of proposals from IVS Member Organizations. On a two-thirds vote the Directing Board may call for new proposals for any Coordinator when it determines that a new Coordinator is required. Coordinators are encouraged to give at least six months notice before resigning.

4.3 Elections

Election of Board members from the IVS components shall be conducted by a committee of three Directing Board members, the chair of which is appointed by the chair of the Directing Board. The committee solicits nominations for each representative from the relevant IVS components. For each position, the candidate who receives the largest number of votes from the Associate Members will be elected. In case of a tie the Directing Board will make the decision.

4.4 Chair

The chair is one of the Directing Board members and is elected by the Board for a term of four years with the possibility of reelection for one additional term. The chair is the official representative of IVS to external organizations.

4.5 Decisions

Most decisions by the Directing Board are made by consensus or by simple majority vote of the members present. In case of a tie, the chair decides how to proceed. If a two-thirds quorum is not present, the vote shall be held later by electronic mail. A two-thirds vote of all Board members is required to modify the Terms of Reference, to change the chair, or to replace any of the members before their normal term expires.

4.6 Meetings

The Directing Board meets at least annually, or more frequently if meetings are called by the chair or at the request of at least three Board members. The Board will conduct periodic reviews of the IVS organization and its mandate, functions, and components.

5 Definitions

5.1 Member Organizations

Organizations that support one or more IVS components are IVS Member Organizations. Individuals associated with IVS Member Organizations may become IVS Associate Members.

5.2 Affiliated Organizations

Organizations that cooperate with IVS on issues of common interest, but do not support an IVS component, are IVS Affiliated Organizations. Affiliated Organizations express an interest in establishing and maintaining a strong working association with IVS to mutual benefit. Individuals affiliated with IVS Affiliated Organizations may become IVS Corresponding Members.

5.3 Associate Members

Individuals associated with organizations that support an IVS component may become IVS Associate Members. Associate Members take part in the election of the incoming members of the Directing Board representing the IVS components.

5.4 Corresponding Members

IVS Corresponding Members are individuals who express interest in receiving IVS publications, wish to participate in workshops or scientific meetings organized by IVS, or generally are interested in IVS activities. Ex officio Corresponding Members are the following:

- IAG Secretary General
- Chair of GGOS
- President of IAG Commission 1 – Reference Frames
- President of IAG Commission 3 - Earth Rotation and Geodynamics
- President of IAU Division I – Fundamental Astronomy
- President of IAU Commission 8 – Astrometry
- President of IAU Commission 19 – Rotation of the Earth
- President of IAU Commission 31 – Time
- President of IAU Commission 40 – Radio Astronomy
- President of URSI Commission 52 – Relativity in Fundamental Astronomy
- President of URSI Commission J – Radio Astronomy

Individuals are accepted as IVS Corresponding Members upon request to the Coordinating Center.

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Links to Additional IVS Information

This page provides links to information about the individuals and groups that support IVS. Member organizations are organizations that support one or more permanent components. Permanent components are groups that formally commit to provide support in one of six categories: coordination of network operations (Operation Centers), collection of VLBI data (Network Stations), processing of raw data (Correlators), archival and distribution of data and products (Data Centers), analysis of data and generation of products (Analysis Centers), and development of new technology (Technology Development Centers).

Associate Members are individuals that are associated with a member organization and have been granted Associate Member status. Associate Members generally support IVS by participating in the activities of one or more components.

Affiliated organizations cooperate with IVS on matters of common interest but do not support a component.

Information Category	Link
Associate Members	
(listed alphabetically by last name)	ivscc.gsfc.nasa.gov/about/org/members/assoc_name.pdf
(listed alphabetically by their organization's country)	ivscc.gsfc.nasa.gov/about/org/members/assoc_org.pdf
Permanent Components	
Network Stations	https://ivscc.gsfc.nasa.gov/about/org/components/ns-list.html
Operation Centers	https://ivscc.gsfc.nasa.gov/about/org/components/oc-list.html
Correlators	https://ivscc.gsfc.nasa.gov/about/org/components/co-list.html
Data Centers	https://ivscc.gsfc.nasa.gov/about/org/components/dc-list.html
Analysis Centers	https://ivscc.gsfc.nasa.gov/about/org/components/ac-list.html
Technology Development Centers	https://ivscc.gsfc.nasa.gov/about/org/components/td-list.html
Member Organizations	https://ivscc.gsfc.nasa.gov/about/org/members/memberorgs.html
Affiliated Organizations	https://ivscc.gsfc.nasa.gov/about/org/members/affilmemberorgs.html