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.

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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 $\sim17^\circ$ 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 terrestrial 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 *νSolve* and *vgosDB* software. *νSolve* 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 *νSolve* 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 *νSolve* 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.

‘Second Epoch VLBA Calibrator Survey Observations: VCS-II ’, D. Gordon, C. Jacobs, A. Beasley, A. Peck, R. Gaume, P. Charlot, A. Fey, C. Ma, O. Titov, and D. Boboltz, Astronomical Journal, 151:154, 2016. doi:10.3847/0004-6256/151/6/154.

‘Impact of the VLBA on Reference Frames and Earth Orientation Studies’, D. Gordon, Journal of Geodesy, 2016. doi 10.1007/s00190-016-0955-0.

‘Observing Gaia transfer sources in R&D and RDV sessions’, K. Le Bail, D. Gordon, J. M. Gipson, D. S. MacMillan, in ‘Proceedings of the 22nd Meeting of the EVGA’, 2015, Ponta Delgada, Azores, R. Haas and F. Colomer (editors), pages 277–280, 2015.

‘Selecting Sources that Define a Stable Celestial Reference Frame with the Allan Variance’, K. Le Bail, D. Gordon, C. Ma, IVS 2016 General Meeting Proceedings, D. Behrend, K. D. Baver, and K. L. Armstrong (editors), NASA/CP-2016-219016, pages 288–291, 2016.

‘IVS Observation of ICRF2-Gaia Transfer Sources’, K. Le Bail, J. M. Gipson, D. Gordon, D. S. MacMillan, D. Behrend, C. C. Thomas, S. Bolotin, W. E. Himwich, K. D. Baver, B. E. Corey, M. Titus, G. Bourda, P. Charlot, A. Collioud, Astronomical Journal (AJ), 151, 3, 79, 2016. doi:10.3847/0004-6256/151/3/79 (http://stacks.iop.org/1538-3881/151/i=3/a=79).

‘The CONT Campaigns as a Precursor to VGOS Observing’, D. MacMillan, ‘Proceedings of the 22nd Meeting of the EVGA’, 2015, Ponta Delgada, Azores, R. Haas and F. Colomer (editors), pages 189–193, 2015.

‘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.