GSFC VLBI Analysis Center Report

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Abstract This report presents a description of the GSFC VLBI Analysis Center and its activities during 2019 and 2020. 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. We continued to support the International Mass Loading Service (atmosphere pressure loading, hydrology loading, and nontidal ocean loading), the Network Earth Rotation Service, and the International Path Delay Service (troposphere raytraced delays for VLBI sessions). Data and information files include VMF1/VMF3 TRP files for every IVS session, the IVS Source Name Translation Table, various station information files, a file of source and station a prioris, a mean gradients file, a JPL planetary ephemeris file for *Calc/Solve/νSolve*, and several other files.

1. NVI, Inc.
2. NASA Goddard Space Flight Center
3. Science Systems and Applications Inc.

GSFC Analysis Center

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2 Analysis Center Staff

In 2019, the staff consisted of one GSFC civil servant and six NVI, Inc. employees who worked under contract to GSFC. Dr. Leonid Petrov, the civil servant, was the GSFC VLBI Lead Scientist. Dr. John Gipson was the GSFC VLBI Project Manager for NVI, as well as the IVS Analysis Coordinator and an IVS Directing Board member. The other NVI employees were Dr. Daniel MacMillan, Dr. Sergei Bolotin, Dr. David Gordon, Dr. Karine Le Bail, and Ms. Karen Baver. In 2020, Dr. Nlingi Habana of Science Systems and Applications Inc. joined the Analysis Center, and Le Bail and Gordon departed. They now work at the Chalmers University of Technology and the U.S. Naval Observatory, respectively. We are grateful for their many contributions and the time we spent with them. The Analysis Center hosted interns Hanna Ek and Rickard Karlsson in 2019 and Cody Hesse and Ugne Miniotaite in 2020.

3 Software Development

The GSFC VLBI Analysis Center develops and maintains the *Calc/Solve* analysis system, a package of $\sim$120 programs and 1.2 million lines of code. Several new versions were released in 2019–2020. Important new features of *Solve* are the abilities to apply antenna gravitational deformation models, new high frequency EOP models, and galactic aberration. *Solve* was modified to allow users to analyze VGOS broadband sessions.

S. Bolotin continued development of *νSolve* and the *vgosDB* software and utilities. *νSolve* is now fully operational and replaces the legacy interactive *Solve* program. These utilities, as well as *νSolve*, are distributed in one package called "nusolve" and are available at https://sourceforge.net/projects/nusolve.

S. Bolotin developed a utility for extraction of various station calibrations (e.g., system temperature, phase calibration) from the field system log file of a station. This information will allow the monitoring of station performance.

L. Petrov incorporated support of linear polarization and mixed polarization observations in the NASA VLBI visibility analysis software tool PIMA. Work continued on improving the robustness of the computation of the polarization complex bandpass.

L. Petrov and N. Habana added new simulation capabilities to a pSolve data analysis tool that accounts for 2D source modeling, elevation dependence of SEFDs, and atmosphere turbulence.

H. Ek and R. Karlsson developed Python scripts to display vgosDB information. C. Hesse worked on a script to help to ingest data at the IVS Data Centers. U. Miniotaite worked on scripts to extract and display Tsys information.

4 Analysis Activities

The GSFC VLBI Analysis Center analyzes all IVS sessions using the *Calc/Solve/νSolve* system and performs the *fourfit* fringing and *Calc/Solve/νSolve* analysis of the VLBA-correlated RDV and other VLBA sessions. The group submitted analyzed databases to IVS for all R1, RV, R&D, AUST, AUG, AOV, AUA, APSG, CRF, CRDS, INT01, INT03, and INTVI sessions.

During 2019–2020, GSFC analyzed approximately 379 24-hour IVS sessions and approximately 847 one-hour UT1 sessions (INT01, INT02, and INT03). With the advent of broadband observing, GSFC analyzed 38 24-hour broadband VGOS sessions and 11 VGOS UT1 (INTVI) sessions. Updated EOP and daily Sinex files were submitted to IVS immediately following analysis.

D. Gordon and D. MacMillan, with assistance from K. Baver, generated quarterly solutions 2019a, 2019d, 2020a, 2020b, and 2020c, which provided 24-hour global, 24-hour baseline, and Intensive plots and data.

D. Behrend et al. wrote a paper describing the efforts required to organize the CONT17 campaign [5].

5 Research Activities

5.1 Reference Frames

As the IVS Analysis Coordinator, J. Gipson directed the efforts of Analysis Centers to generate ITRF2020 solutions for the IVS Combination solution. Eleven Analysis Centers submitted solutions, which included S/X sessions from 1979–2020 as well as VGOS sessions (CONT17 and sessions from 2019–2020). Among the ACs, seven different software packages were used. D. MacMillan generated the GSFC solution using Calc/Solve.

Three NVI personnel (D. Gordon, S. Bolotin, and D. MacMillan) actively participated in the generation of ICRF3 as members of the IAU ICRF3 Working Group. The ICRF3 group wrote a paper on ICRF3 and its generation [8].

D. MacMillan, as chair of the IVS Galactic Aberration Working Group, wrote a paper along with group members summarizing their investigation [12]. The paper recommended the galactocentric acceleration constant that was then used to generate the ICRF3 solution.

K. Le Bail continued to monitor the proposed 195 Gaia transfer sources. She wrote a report on the seven years of the R&D sessions for review by the OPC to show the progress of the program.

K. Le Bail worked with PI Alet de Witt to select the optimal station network for the CRF sessions to strengthen the southern hemisphere of ICRFs.

5.2 Source Structure

L. Petrov along with co-authors showed that VLBI-Gaia (optical) source position offset angles are nearly uniform over the sky. The VLBI-Gaia offset directions were shown to be correlated with jet direction [14]. Work continued on the study of the systematic differences between VLBI and Gaia source position differences. New strong evidence was obtained that confirms the initial hypothesis that observed position offsets are manifestations of optical jets [16].

L. Petrov and F. Schinzel continued VLA and VLBA multi-frequency monitoring of 3C48. They found brightening and dimming of the stationary component within 1.5 mas of the core. A paper is in preparation.

S. Bolotin analyzed the VGOS CONT17 broadband sessions, which revealed the effects of source structure in the group delay residuals. To take this effect into account, Bolotin developed a multi-point source structure model and implemented it in *νSolve* [6].

S. Bolotin wrote a paper on source structure effects in CONT17 VGOS observations (submitted 2019). He found that broadband delays are radio source brightness distributions and developed source structure models of sources that had large systematic residuals. Application of the models removed these systematic variations.

K. Le Bail compared the noise floor of the sources in the S/X catalog with the noise floor of the sources in the K-band catalog [11].

K. Le Bail worked with Leonid Petrov on the selection of sources from Petrov's RFC catalog that are strong and compact, and that show no apparent structure, as candidates for the good geodetic source catalog. Thirty seven of these sources were added to the good geodetic catalog in May 2020.

5.3 Observing Surveys

A decade-long observing campaign (LCS2) using a network of radio telescopes in Australia, New Zealand, and South Africa resulted in elimination of the hemisphere bias where the number of compact radio sources in the Southern hemisphere was much less than the Northern hemisphere. Elimination of the bias improves the capability of maintaining the terrestrial reference frame. L. Petrov et al. discussed the results of this program in [13].

L. Petrov and colleagues continued observation programs of pathfinder VLBI astrometry surveys, VCS10 and VCS11, that along with other observing programs added 3,666 new VLBI-detected sources. Positions and images have been derived from the data of the VCS10 program. A paper is in preparation.

Popkov et al. studied VLBI data from the Northern Polar Cup Survey and the population of the unbiased sample of sources drawn from the parent NVSS catalog without selection based on spectral index [17].

L. Petrov and colleagues have completed the SOuthern Astrometric Program for improving the positions of 217 southern sources. A paper is in preparation.

L. Petrov and colleagues ran the KVN observing program "A search for high-frequency calibrators within 10 degrees of the Galactic center" at 22 and 43 GHz. They have detected 91 previously known compact sources and 24 new sources. They are also running the VLBA program "K- and Q-band VLBI Calibrators near the Galactic Center" with the goal of improving the positions of 115 sources within 10 degrees of the Galactic center detected with the KVN.

In addition, L. Petrov carried out "The wide-field VLBA calibrator survey – WFCS" [15] and was involved in research on microarcsecond VLBI pulsar astrometry with PSRpi [9].

5.4 Gamma Ray Sources

S. Bruzewski et al. continued a VLA and ATCA program of observations of Fermi unassociated sources [7]. They conducted the LBA observing program "Unveiling the nature of gamma ray sources in the 4FGL catalogue - LBA Observations" that is the follow-up of prior ATCA observations.

L. Petrov participated in a further survey of unassociated gamma ray objects in the seven-year Fermi/LAT catalog, which found 310 associated gamma ray sources. In total, VLBI association was found for 54% of extragalactic objects. Redshifts were determined for 28% of Fermi gamma ray sources via VLBI association [1]. Among gamma ray loud AGNs, a VLBI association was found for 90% of the sources [2].

5.5 Galactic Gravitational Field

L. Petrov was involved in a study of the impact of the non-stationarity of the gravitational field in the Galaxy on precise astrometry. They found that this effect causes a jitter in source positions that is potentially observable. This jitter sets a fundamental limit of astrometric accuracy that space flight at distances of several kiloparsecs is required to overcome [10]. They ran a pilot program with the KVN for detection of the background position noise due to the non-stationarity of the Galactic gravitational field at 22 GHz.

5.6 Intensive Sessions

K. Baver finished studying the effect of source flux catalog latency on S/X Intensive schedules [3]. Baver and J. Gipson finished evaluating the “BA 50” strategy of using 50 sources chosen to balance source strength and sky coverage in S/X Intensive schedules [4].

K. Baver ran simulations with the goal of improving S/X or VGOS Intensive scheduling. She scheduled 22 VGOS INTVI sessions, some of which also tested schedule configuration changes suggested by GSFC and MIT personnel.

5.7 Analysis Comparisons

S. Bolotin developed a script to process S/X INT sessions automatically for the purpose of comparing automated and manual analysis of these sessions. Tests applying this script to all INT sessions from the latest three years show that just a few percent of sessions need to be processed manually: for the remaining sessions, the results from automatic processing are the same as from manual processing. Eskil Varenius from Onsala Space Observatory used a similar script to process ultrashort VGOS sessions (with three Onsala antennas) as well as VGOS INT sessions that were correlated at the Onsala Space Observatory.

S. Bolotin and J. Gipson made comparisons of a VGOS session (24-hr VGOS session VO0009) correlated at Bonn and Haystack. In the end, the results using the two correlations yielded two very close (but not identical) solutions. A second test was done for INT VGOS session 20DEC15VI and compared the correlations from USNO (Washington, DC) and the TUV (Vienna, Austria). Both databases were practically identical except for the calculation of the PCMT cable corrections.

5.8 Miscellaneous Topics

Krásná and Petrov processed data from the astronomical VLBA program MOJAVE at 15 GHz in geodetic mode. They estimated baseline repeatability and compared it with repeatability from geodetic VLBA sessions at 2.3/8.4 GHz. They also evaluated quantitatively the impact of the residual ionosphere on baseline repeatability from single band 15-GHz observations (H. Krásná et al, 2021, in preparation).

Kierulf et al. performed quantitative analysis of the effect of glacial loading on the positions of the VLBI and GNSS stations at Svalbard, Norway. They found that the disagreement between the predicted and observed vertical seasonal signals is at the level of 5% (H. Kierulf et al, 2021, in preparation).

Ray et al. computed mass loading from the ψ_1 tide and evaluated its impact on nutation [18].

L. Petrov and N. Habana investigated the feasibility of using ngVLA for space geodesy. They modified the pSolve software to support an experiment with up to 256 sources and started processing a simulated dataset from ngVLA. The focus of the study is to evaluate the impact of routine ngVLA observations that include observations of strong calibrators on geodesy.

J. Gipson chaired an IERS Working Group on HF-EOP. The goal of this Working Group was to recommend a replacement for the current IERS model, which was 20 years old. The new model will be used for ITRF2020. Gipson gathered ten different HF-EOP models and put them in a common format. He also wrote software to calculate the predicted HF-EOP. As of the end of 2018, tests done using VLBI and GPS data indicated that the two best models are one based on TPX 8 altimetry data by Desai and Sibois, and an empirical model based on VLBI data by Gipson. The final recommendation was to use the Desai and Sibois model.

D. MacMillan investigated the differences between EOP and TRF scale parameters estimated from the simultaneous observing sessions of the two legacy and the VGOS networks. A paper was submitted to the Journal of Geodesy (VLBI special issue).

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