GSFC VLBI Analysis Center Report

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Abstract This report describes the GSFC VLBI Analysis Center and its activities during 2021 and 2022. The GSFC VLBI Analysis Center analyzes all IVS sessions, makes regular IVS submissions of data and analysis products, performs limited scheduling, and performs research and software development aimed at improving the VLBI technique.

1 Introduction

The GSFC VLBI Analysis Center (AC) is located at NASA's Goddard Space Flight Center in Greenbelt, Maryland, USA. It is part of a larger VLBI group which also includes the IVS Coordinating Center, the CORE Operation Center (OC), 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, and it schedules a VGOS Intensive series. The AC supports several services, including 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). The AC maintains several important data and information files for the IVS and the larger geodetic community, including VMF1/VMF3 TRP files for every IVS session, various station information files, a mean gradients file, and a JPL planetary ephemeris file for *Calc/Solve/νSolve*.

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

GSFC Analysis Center

IVS 2021+2022 Biennial Report

2 Staff

The staff consists of two GSFC civil servants and six staff members who work under contract to GSFC. The first civil servant, Dr. Leonid Petrov, is the GSFC VLBI Lead Scientist. He engages in a variety of VLBI research and software development activities. The second civil servant, Dr. Frank Lemoine, participates in the planning, execution, and monitoring of VLBI experiments. He also focuses on the derivation of the ITRF, reducing the systematic error in each of the techniques of Space Geodesy. Five of the contractors work for NVI, Inc. They are Dr. John Gipson (who is the GSFC VLBI Project Manager for NVI, as well as the IVS Analysis Coordinator and an IVS Directing Board member), Karen Baver, Mario Bérubé, Dr. Sergei Bolotin, and Dr. Daniel MacMillan (now working part time), The final contractor is Dr. Nlingi Habana of Science Systems and Applications, Inc.

The AC hosted six interns in 2021 and 2022. Four came from Sweden's Chalmers University of Technology: Adrian Lundell and Samuel Wagner (remotely, in 2021) and Tuss Anzelius and Ludvig Rodung (2022). The others were Simon Matin (University of New Mexico, 2022) and Joseph Skeens (University of Texas at Austin, 2022).

3 Software Development

The GSFC VLBI AC develops and maintains the *Calc/Solve* analysis system, a package of ∼120 programs and 1.2 million lines of code. The AC released three new versions in 2021 and 2022. Important new *Solve* features include the ability to use the new Post-Seismic Deformation models from ITRF2020, support for source structure in vgosDB, increased precision in various a priori files, and the ability to override the default "near" distance in applying pressure loading displacements. Further information is available in each *Calc/Solve* version's release notes.

Bolotin continued the development of *νSolve* and the *vgosDB* software and utilities, including the following four features. Matrix triangularization calculations in *νSolve* are now done in parallel for speed, using POSIX threads. Bolotin also developed a Java script to simulate interactive analysis of actual observed Intensive sessions, and a comparison of the script's output to five years of Intensive interactive analysis by analysts (2,494 sessions) gave identical results for half the sessions and scaled dUT1 estimate differences between −1 and +1 for 87% of the sessions (Bolotin et al. 2023). Bolotin also updated *νSolve* and the *vgosDB* utilities to handle the new post-2022 master schedule format and IVS session naming convention. Finally, Bolotin replaced third party code in *νSolve* with his own code. The latest *νSolve* code was split into a *νSolve* package and a *libCalc* package that contains the *Calc* source code. These packages are available at https://sourceforge.net/projects/nusolve and https://sourceforge.net/projects/libcalc, respectively.

Bérubé developed software to finish operational processing after *νSolve* analysis (*APS*). *APS* combines the functions of the earlier *Opa* and *Anl_comments* programs, e.g., generating EOP and SINEX files, submitting vgosDB, EOP, and SINEX files to IVS, and generating analysis report templates. Bérubé continued to maintain the *Vget* script, which downloads and preprocesses new sessions.

Gipson continued development of *SimpleSimul*, a simulation program. This program can compare the performance of different networks, and it is used by the CORE Operation Center in developing the Master Schedule. It can also be used to compare different schedules using the same network. The CORE OC uses *SimpleSimul* in this fashion to schedule some Intensive sessions.

Habana and Petrov began to develop a software package, *ATP*, to study the baseline telemetry metrics at NASA-managed VLBI stations. This study involves running weekend-long single-dish experiments at each station in stow position, transforming the log file to an ASCII antenna calibration (.anc) file with the *νSolve log2ant* routine, and converting the .anc file to a binary format (.bnc) file. Then scan averages and their respective root mean errors are computed and written back to ASCII format. Although the *ATP* library extracts all telemetry data from the log file, the statistical analysis is only done on the Tsys, phase calibration, and formatter clock difference data thus far. It will be expanded to include the SEFD data.

Five interns developed software. Anzelius and Rodung developed Python scripts to generate source-flux models from source images. Lundell developed Python scripts to compute the Helmert transformation between two reference frames. Skeens wrote a tool to automate the detection of spurious signals in VLBI phase calibration data. Wagner enhanced Python *vgosDB* utilities to make them faster.

4 Analysis Activities

The GSFC VLBI AC analyzes all IVS sessions using the *Calc/Solve/νSolve* system. The AC submitted analyzed databases to IVS for all R1, RV, R&D, AUST, AUG, AOV, AUA, APSG, CRF, CRDS, INT01, INT03, and VGOS sessions. In 2021 and 2022, Bolotin and Baver analyzed approximately 490 S/X and 73 VGOS 24-hour sessions and approximately 944 S/X and 428 VGOS one-hour UT1 sessions when they were initially correlated. This breakdown categorizes the sessions by whether they were primarily S/X or VGOS, but some of the sessions were actually mixed mode. Updated EOP and daily SINEX files were submitted to IVS immediately following analysis. The AC re-analyzed many sessions after the late submission of stations or other circumstances.

Baver used *Calc/Solve* to generate csolve quarterly solutions 2021a–2021d, which provided 24-hour global, 24-hour baseline, and Intensive plots and data. She began work on the 2022a solution but placed this on hold while Gipson investigated a slope in the estimated X-wobble with respect to USNO finals. Petrov used his *Solve* version, *Psolve*, to generate solutions psolve 2021a–2021d and 2022a–2022c. Baver generated auxiliary (e.g., baseline evolution) files for these solutions.

5 Research Activities

EOP and Scale Parameter Comparison: MacMillan compared EOP and scale parameters that were estimated from the CONT17 session involving two legacy networks and a VGOS network (MacMillan 2022). He determined that the biases between EOP estimates from the three networks were mostly at the 1-sigma level. Three-corner hat analysis of polar motion from the two legacy networks and the IGS Finals GNSS series indicated that the precision of the Legacy 1 network was only slightly less than the precision of the GNSS series over the CONT17 observing period. Baseline length repeatabilities at the level of 0.4 ppb for the relatively small demonstration VGOS five station network were a little better than those for the two legacy networks.

MACGO12M–WETTZ13S Intensives: Lemoine and Petrov participated in an R&D VLBI Intensive program, VGOS-INT-S, which observed the MACGO12M–WETTZ13S baseline for the rapid determination of the Earth's phase of rotation, expressed as UT1-UTC (Schartner et al. 2023). The observation series in 2022 consisted of 25 one-hour Intensive sessions and six 24-hour Intensive sessions. The one-hour S2 Intensive program used a special observation strategy, the rapid alternation between high- and low-elevation scans, which improves the determination of delays caused by the neutral atmosphere. The 24-hour sessions tested alternate observation strategies for zenith troposphere delay determination. The sessions were scheduled by Mathias Schartner (ETH Zürich) and correlated at Wettzell by Christian Plötz (BKG). In early 2022, the sessions were highly accurate, until multiple technical problems impacted the sessions' performance. The S2 Intensives also typically included approximately 1.5 times as many observations in one hour as the V2 Intensives.

Mauna Kea Earthquake's Effect on UT1-UTC: MacMillan was a co-author of a study by Chris Dieck (USNO) on the effect of the Mauna Kea Earthquake in 2018 on UT1-UTC estimates from Intensive sessions that use the Mauna Kea/PieTown baseline (Dieck et al. 2022). The study showed that the observed UT1 offset was consistent with the displacement of the GNSS station co-located with the Mauna Kea VLBA antenna. The GNSS position can therefore be used to correct the a priori position of the VLBI station, which is critical for maintaining the accuracy of UT1-UTC. Without a co-located GNSS receiver, the VLBI station position model would likely not be modified for months.

Midnight Intensives: Gipson was involved in studying S/X Intensives centered around 0:00 UT. The rationale for this series is that interpolation is not required to compare them to external series, which generally report values at 0:00 UT or at 0:00, 6:00, 12:00, and 18:00 UT. Preliminary studies indicated that the midnight Intensives performed as well as the standard Intensives in terms of precision. Because the midnight Intensives are observed five hours later than the standard Intensives, latency was a potential concern, but this turned out not to be an issue.

R1 and R4 Performance: Cynthia Thomas (CORE OC, GSFC), MacMillan, and Karine Le Bail (Onsala) wrote a paper about the performance of the R1 and R4 sessions (Thomas et al. 2022). The paper investigated the evolution of these series from 2002.0 to 2020.0 in terms of their observing networks, discussed the construction and scheduling of sessions, and determined the precision of polar motion and UT1. Since 2002.0, the precisions of polar motion and UT1 improved by a factor of 2–3 and 1.5, respectively. The main reason for the improvement was the increased size of the networks.

Reference Frames: As the IVS Analysis Coordinator, Gipson directed the efforts of the IVS ACs during the final stages of submitting the data for ITRF2020. Eleven ACs submitted solutions, which included S/X sessions from 1979–2020, as well as VGOS sessions (CONT17 and sessions from 2019–2020). Gipson also chaired ad hoc IVS Working Groups on the evaluation of ITRF2020P (the preliminary version of ITRF2020) and wrote the report summarizing their findings.

RFI Mitigation: Habana was involved in tasks for developing a dynamic mask to mitigate the threat of spaceborne radio frequency interference (RFI). Such a mask is especially necessary when considering the exponential growth of low Earth orbiters that provide Internet downlinking within the same frequency band as the VGOS spectrum. Habana developed routines for converting Two Line Elements (TLE) to cartesian coordinates based on [1] and subsequently to a satellite's look angles from a given station.

Satellite Threat Database: Habana is responsible for the development of a database to host information about any satellite that may pose a threat to VLBI observations. Matin assisted in combing through the FCC website and perusing the documents of each satellite constellation of interest. This information was used to update the database of over 2,000 satellites. It includes, but is not limited to, the satellite's designated frequency band(s), Effective Isotropic Radiated Power (EIRP), polarization, and emitter. From the winter of 2021 through the fall of 2022, Habana, with assistance from Lawrence Hilliard (GSFC) and Derek Hudson (GSFC), made multiple observations to track spaceborne RFI sources using a field antenna at the Goddard Geophysical and Astronomical Observatory (GGAO).

Scale: Zuheir Altamimi (IGN) reported anomalous behavior of the VLBI scale after about 2014 with respect to ITRF2020. Gipson chaired an ad hoc working group to study this. IVS ACs see this scale difference with respect to ITRF2020. But if they use a VLBI-derived reference frame as an a priori, the effect disappears.

Schedule Characteristics: Wagner used machine learning to analyze Intensive schedules to search for common characteristics of successful schedules.

VGOS Intensive Scheduling Simulations: Baver investigated the expected number of observations if NYALE13N is tagged onto the KOKEE12M–WETTZ13S baseline. She also evaluated the effect of a warm receiver at GGAO12M, KOKEE12M, MACGO12M, and WESTFORD in turn.

6 Scheduling Activities

Baver, Gipson, and Petrov were involved in a pilot program in 2021 and 2022 that studied VGOS Intensives using the KOKEE12M (K2) and WETTZ13S (Ws) antennas. Baver scheduled more than 300 V2 K2-Ws VGOS Intensives for the same time as the INT01 S/X Intensives that the NEOS OC scheduled using KOKEE and WETTZELL. The VGOS Intensives performed much better than the S/X ones. For example, the RMS difference of the UT1 estimated from the VGOS sessions and temporally close R1 and R4 sessions was 16 µs, while it was 25 µs for the S/X sessions.

The V2 series observed K2 and Ws, unless one of those stations could not observe. Baver wrote schedules for ten GGAO12M–KOKEE12M, four ISHIOKA–WETTZ13S, and ten KOKEE12M–ONSA13NE V2 sessions.

Improvements to scheduling focused on the K2/Ws baseline. The main improvement was increasing the number of scheduled observations. Baver and Gipson ran simulations that determined that this could be accomplished by decreasing the maximum scan length from 200 to 60 seconds and by decreasing the target SNRs from 20 to 15 to compensate for the decreased number of available sources under the decreased scan length. This change was implemented in January 2022 and evaluated in Gipson et al. 2023 and Baver et al. 2023. Baver also ran simulations to evaluate the robustness of the K2–Ws schedules under a warm receiver at either or both stations. This resulted in a change to the SEFDs used in scheduling. Finally, Baver began to update the source list used in scheduling the K2–Ws sessions. She replaced a weak source with a stronger source, and she began to investigate an alternative source list from Petrov.

Baver also ran a simulation to determine which of eight combinations of maximum scan lengths and target SNRs would generate the highest average number of scheduled GGAO12M/KOKEE12M observations. She used this information for writing the ten GGAO12M/KOKEE12M schedules.

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