GSFC VLBI Analysis Center Report

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Abstract The Goddard Space Flight Center 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. This report describes the GSFC VLBI Analysis Center and some of its activities during 2023 and 2024.

1 Introduction

The Goddard Space Flight Center VLBI Analysis Center (GSFC 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, a Technology Development Center, and a VGOS station. The AC participates in all phases of geodetic and astrometric VLBI analysis, software development, and research. The AC supports several services, including the International Mass Loading Service (atmosphere pressure loading, hydrology loading, and nontidal ocean loading). The AC maintains several important data and information files for IVS and the larger geodetic community, including VMF1/VMF3 TRP files for every IVS session, various station information files, and a mean gradients file. This report describes the GSFC VLBI Analysis Center and some of its activities during 2023 and 2024.

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

GSFC Analysis Center

IVS 2023+2024 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, Karen Baver, Mario Bérubé, Dr. Sergei Bolotin, and Dr. Gönenç Moğol, who joined the group in November 2024. The final contractor is Dr. Nlingi Habana of Science Systems and Applications, Inc. Dr. Daniel MacMillan left in 2023 to pursue other interests, withdrawing his expertise and cheerful personality.

The AC hosted six interns in 2023 and 2024. Four came from Sweden's Chalmers University of Technology: Samuel Collier Ryder and Filip Herbertsson (2023) and Lisa Höllander and Lisa Vind (2024). The other interns were returning intern Joseph Skeens (University of Texas at Austin, 2023) and Henry Arthur (Drew University, 2024).

3 Software Development

The GSFC AC develops and maintains the *Calc/Solve* analysis system, a package of $\sim$120 programs and 1.2 million lines of code. Gipson made many changes to the package, and the AC released three new *Calc/Solve* versions in 2023 and 2024: csolve_2023-01-15,

csolve_2023-10-31, and csolve_2024-10-31. Highlights from the three releases include the following:

- Support for IVS' January 2023 master schedule format and session naming convention (csolve_2023-01-15),
- Substantial changes to the Snranal program (csolve_2023-01-15),
- More consistent handling of time tags (csolve_2024-10-31),
- A new ability to remove one-second clock breaks on the fly (csolve_2024-10-31),
- A new batch control file $SETUP section option, MOD_TIME, which sets the epochs for the piecewise-linear estimation of atmosphere, clock, or EOP parameters (csolve_2024-10-31),
- The introduction of a new version of the TRP file format, which includes the wet and dry zenith delay and the wet and dry mapping functions (csolve_2024-10-31).

Calc/Solve users should consider checking the new releases' release notes for more details. The release notes for a *Calc/Solve* version "csolve_yyyy-mm-dd" are usually in the distribution's release directory, release, e.g. as Solve_release_yyyy-mm-dd.docx and Solve_release_yyyy-mm-dd.pdf. But the notes for the 2023-10-31 release were incorporated into the notes for the 2024-10-31 release. The release directory also contains the release notes for many earlier releases.

Petrov maintains an alternate analysis system named *Psolve*. Interested users should contact him for details.

Bolotin continued development of *νSolve* and the *vgosDB* software and utilities. Most of the updates supported a related script, autoINT.js, that performs automated processing of Intensive sessions, but Bolotin also implemented the generation of VMF3 (Vienna Mapping Function) files for sessions. The software is now distributed as a single package containing:

- νSolve — a GUI tool for analyzing new VLBI sessions,
- vgosDbMake — a utility for creating a vgosDB database from fourfit files,
- vgosDbProcLogs — a utility that extracts meteorological data and cable calibration corrections from a field system station log file and adds the data to a vgosDB database,
- log2ant — a utility that parses a field system log file, extracts various telemetry data, and stores the data in an ASCII file (in the ANTCAL format).

The package is available at the following address: https://sourceforge.net/projects/nusolve

Bérubé continued development and maintenance of the *Vget* script, which downloads and pre-processes new sessions, and the *APS* (Automated Post Solve) application, which finishes operational processing after *νSolve* analysis. Bérubé improved Vget to automatically process all Intensive sessions by processing their data using νSolve and by generating products, vgosDB files, and reports using APS and submitting them to IVS. He also modified Vget to detect false session submissions. Bérubé improved APS to better integrate correlator comments into analysis reports. He also modified APS to replace the UT1 formal errors with the simulated UT1 RMS scatter (calculated by *SimpleSimul*) for VGOS sessions.

Gipson continued to develop the *SimpleSimul* simulation program. *SimpleSimul* is used by the CORE Operation Center in developing the Master Schedule. *SimpleSimul* is now used routinely to provide the simulated UT1 RMS scatter for the VGOS sessions in operational processing. The program is also used in generating the IVS-INT-00 ("midnight") Intensive schedules.

Habana and Petrov developed a library for processing antenna telemetry (ATP) to study the baseline telemetry metrics at NASA-managed VLBI stations. This study involved running weekend-long single-dish experiments (SDE) at each station and tying these to the mid-week VGOS experiments. Extensive details of this library package and how Habana and Petrov continue to update it have been reported in Habana and Petrov (2025) [8].

The 2023 and 2024 Chalmers interns continued to develop scripts written by the 2022 Chalmers interns, Tuss Anzelius and Ludvig Rodung, to generate source flux models from source images. In 2023, Collier Ryder and Herbertsson worked on updating the scripts to compare source flux densities from Gaussian models to measured densities. In 2024, Höllander and Vind made three changes to the scripts. First, the scripts had modeled source images with data from fits files as a sum of Gaussian distributions, using least squares. Höllander and Vind introduced the physical coordinate system of a source to the models by scaling the resulting Gaussian distributions. Also, Vind and Höllander recalcu-

lated the visibility function to include an explicit dependency on the angular frequency, in order to get an analytical expression for the group delay. Vind and Höllander then fit the group delay to a plane using least squares, and they calculated the root mean square error with respect to the fitted plane. Finally, Höllander and Vind developed a new GUI to display the results, because the scripts had been using a free Python library that later became licensed.

Herbertsson and Collier Ryder wrote a Python script to plot length, transverse, and horizontal baseline values over time. The script can automatically remove outliers and fit trendlines to plots. The script can be run either by using a GUI or in script mode.

Collier Ryder and Herbertsson wrote a utility to merge vgosDB information (e.g., from different institutions) from the same session.

Herbertsson and Collier Ryder wrote a program to calculate and visualize SNRs and flux densities for the VGOS A, B, C, and D bands. The program can be run using a GUI or in script mode. It operates on both VGOS and S/X sessions.

Skeens wrote a diagnostic tool to bootstrap individual phase delay solutions for each intermediate frequency band. The tool can be used to search for systematic bias in S-band and X-band.

4 Analysis Activities

The GSFC AC analyzes all IVS sessions using *νSolve*. During 2023 and 2024, Bolotin and Baver analyzed the 24-hour sessions manually. They also analyzed the one-hour (Intensive) sessions manually until mid-2023, when the AC began to analyze the Intensive sessions in automatic mode, with Bolotin and Baver intervening manually where necessary. For this purpose, the AC used the ADAP/APS software developed by Bérubé and the autoINT.js script from *ν*Solve. After four months of using autoINT.js, Bolotin revised the script in October 2023 to improve performance based on lessons learned. As a result of transitioning to automatic processing, the median data processing time was reduced from several hours to a few seconds [Bolotin_et_al].

The GSFC AC has calculated that the AC software and analysts analyzed 234 S/X and 167 VGOS 24-hour sessions and 1247 S/X and 807 VGOS one-hour sessions when they were initially correlated, as well as reanalyzing 29 S/X and 59 VGOS 24-hour sessions and 88 S/X and eight VGOS one-hour sessions after the late submission of stations' data or other circumstances. The VGOS category includes mixed-mode sessions. The AC also assessed and reported additional sessions as failed.

The AC submitted analyzed vgosDB file sets to IVS for all session types which the master schedule files designate as part of the AC's responsibility, including AOV, APSG, AUSTRAL, IVS-R1, IVS-RD, VGOS-OPS, and VGOS-RD 24-hour sessions and IVS-INT-00, IVS-INT-1, IVS-INT-3, IVS-INT-S, VGOS-INT-A, VGOS-INT-B, VGOS-INT-C, VGOS-INT-D, VGOS-INT-M, and VGOS-INT-S Intensive sessions. The AC submitted updated EOP and daily SINEX files for all session types to IVS following analysis.

Petrov used his *Solve* version, *Psolve*, to generate solutions psolve 2022d, 2023a–2023d, and 2024a–2024c. Baver generated auxiliary (e.g., baseline evolution) files for the first seven solutions, with a goal of working on the 2024c solution in early 2025. Gipson used *Calc/Solve* to generate csolve quarterly solution 2023a. Baver and Gipson began to work on csolve solution 2024a in late 2024, but by the end of 2024, they were investigating a problem related to comparing the EOP output to external EOP.

5 Research Activities

Geodetic Surveys. Habana engaged in geodetic surveys and other tasks that were previously conducted by the late Jim Long. Habana assisted the National Geodetic Survey (NGS) when they conducted a local tie survey of the space-geodetic techniques at GGAO, the first such survey at the site since 2012. He also went to Fortaleza, Brazil to conduct a geodetic survey before construction of the 12-m antenna began.

GNSS Antenna Use in Radio Interferometers. Skeens, Petrov, and others [9] demonstrated that a GNSS antenna can be used as an element of a radio interferometer. Both artificial satellites and natural radio sources located at gigaparsec distances have been successfully detected.

Jet Stream Impact on UT1. Arthur assessed the impact of the jet stream on UT1. He implemented image segmentation algorithms to extract the jet stream

from meridional cross-sections of zonal wind from the GEOS-FPIT model. Plotting the output allowed for the empirical verification of the jet stream. Arthur also computed the motion term of the jet stream and analyzed its contribution to the atmospheric angular momentum budget for one year of data.

KOKEE12M–ONSA13NE (K2–Oe) Baseline as a Backup for the Baseline KOKEE12M–WETTZ13S (K2–Ws). Baver, Gipson, and Lemoine determined that the KOKEE12M–ONSA13NE baseline could potentially be a viable backup for the KOKEE12M–WETTZ13S baseline. Baver et al. (2025) [1] provides details.

Legacy S/X and VGOS Network Comparisons. Bolotin assisted Cynthia Thomas (CORE Operation Center) in analyzing IVS-R1, IVS-R4, and VGOS-OPS sessions conducted from early 2019 through 2023 (Thomas et al. (2025), [12]). Bolotin then extended the work by a year and used the Vienna Mapping Function (VMF3). Bolotin obtained two solutions: baseline estimation and EOP determination. A comparison of the analysis results shows that baseline repeatability is better for VGOS than for the legacy S/X networks. But the dispersion of EOP estimations from VGOS data is larger than that of the R1 and R4 networks. The conclusion is that the VGOS technique demonstrates strong potential, but the current network geometry is suboptimal, and deploying additional stations is necessary to improve EOP estimates and station coordinate accuracy. Bolotin presented the final work at the Fall 2024 AGU meeting.

Reference Frames. As the previous IVS Analysis Coordinator, Gipson directed the efforts for an ITRF2020 update. This update included the sessions observed during 2021 and 2022, as well as earlier sessions which were not previously analyzed.

RFI. Habana continued to be involved in tasks to mitigate the threat of both terrestrial and spaceborne Radio Frequency Interference (RFI). He continued to manage and update the library for converting Two-Line Elements (TLEs) to a satellite's look angles from a given station. This library is part of the SGDASS public software package. He also continued to monitor and update the database that hosts information about satellites that pose a potential threat to VLBI infrastructure. During this reporting period, he included the monitoring of global navigation satellite systems (GNSS) in the database. The database is updated bi-daily with the latest TLEs and threat levels of the satellites to the station at GGAO. In order to study the changing environment of the (terrestrial) RFI at GGAO, Habana conducted multiple RFI surveys on site between 2023 and 2024. Furthermore, he extended these surveys to French Polynesia to help scout for a potential future VLBI site.

Smoothing Schemes for Cable Calibration Data. Moğol worked on the effects of smoothing schemes for the cable calibration data. He used the Locally Weighted Scatterplot Smoothing (LOWESS) technique with different window sizes in order to capture the variations in the cable calibration data at different time scales. A big advantage of LOWESS smoothing over other smoothing techniques is its resilience to outliers. During the iterative fitting procedure, the data are reweighted in subsequent iterations depending on any given data point's distance to the smoothed curve. Therefore, this technique combines smoothing and outlier detection/removal. Moğol used CONT14 and CONT17 datasets in order to benchmark the smoothing schemes. The efficacy of each smoothing scheme was measured by the baseline scatter of the solution over the entire CONT campaign. He found that for the CONT14 data, the improvement in baseline scatter was marginal, whereas for the CONT17 dataset, smoothed cable calibration data improved the baseline scatter somewhat. But the small improvement of the baseline scatter did not warrant the implementation of the smoothing schemes in the regular data pipeline.

Source Flux Catalog Input Data Ranges. The GSFC AC has thought that four to eight weeks of input data are acceptable for generating a source flux catalog, but Baver has used six weeks as the default value. Now Baver tested source flux catalogs made with four, five, six, seven, or eight weeks of data in VGOS-INT-A scheduling. The testing verified that six weeks of input data is acceptable for VGOS-INT-A scheduling.

Substitution of UT1 Scatter for UT1 Formal Errors in VGOS Intensive Analysis. USNO commented that the formal errors for the VGOS-INT-A Intensive sessions were unrealistically small. Gipson studied the issue and noticed that if the formal errors were replaced with the predicted UT1 scatter determined by *Simple-Simul*, the results were more reasonable. USNO verified these results independently. As a result the VGOS-INT-A sessions are now used in the operational USNO EOP products. The GSFC AC also now has substituted UT1 scatter for the UT1 formal error metric in all operational VGOS Intensive analysis.

Tagging WETTZ13N onto VGOS-INT-A Schedules. Baver generated 12 test schedules to evaluate how many WETTZ13N observations could be expected when WETTZ13N is tagged onto a VGOS-INT-A (KOKEE12M–WETTZ13S) schedule. WETTZ13N can be expected to participate in most WETTZ13S observations, except where a source does not rise in time at WETTZ13N. WETTZ13N will be tagged onto the VGOS-INT-A schedules for a few months starting in early 2025.

VGOS-INT-A Scheduling Improvement. As a carry over from S/X scheduling, VGOS-INT-A schedules have required eight minutes between successive observations of a source. But this is unrealistic for VGOS sessions, which have shorter observations. Baver generated test schedules with two, three, four, five, six, seven, or eight minutes between successive observations of a source, and the testing indicated that a five-minute interval would be best. This change has been implemented in VGOS-INT-A scheduling.

Westford Azimuth Slew Rate. Baver investigated the effect of changing Westford's azimuth slew rate under various conditions (e.g., decreasing the miminum scan length from 30 to 15 seconds) to investigate questions raised by Gipson, Derek Hudson (GSFC), and Pedro Elosegui (MIT).

6 Presentations and Submitted/Accepted/Published Works involving GSFC AC Co-authors

The following list is a partial list of papers and presentations for which GSFC AC staff members were co-authors.

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12. Thomas, C., K. Baver, S. Bolotin, J. Gipson. "Comparison of Operational S/X and VGOS Sessions for EOP Determination", IVS 2024 General Meeting Proceedings, pages 207–211, 2025.