GFZ Analysis Center Report

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Abstract This report provides general information and a component description of the IVS Analysis Center at GFZ. Current activities and recent results are described, and planned future work is outlined.

1 General Information

The GFZ Helmholtz Centre for Geosciences is the national research center for Earth sciences in Germany. Within department 1 "Geodesy", section 1.1 "Space Geodetic Techniques" the working group "Combination and VLBI", led by R. Heinkelmann, unites the former two working groups "Combination of space geodetic techniques" and "Geodetic and astrometric VLBI" established in late 2012 into one working group. Previously, the working group "Combination of space geodetic techniques" was led by S. Glaser until 08/2023 when she moved to the Institute of Geodesy and Geoinformation, University of Bonn.

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GFZ Analysis Center

IVS 2023+2024 Biennial Report

The Combination and VLBI group of GFZ functions as an Associate Analysis Center (AC) of IVS.

Fig. 1 Members of the GFZ working group "Combination and VLBI" in 03/2024 (K. Balidakis, S. Glaser, C. Kitpracha, P. Küreç Nehbit, N. Mammadaliyev, P. Poopat, and E. Tamaryan not pictured in the photograph).

2 Activities during the Past Two Years

The software Potsdam Open-source Radio interferometry Tool (PORT)[21], GFZ's VLBI analysis software package, is used for the operational processing of 24-hour sessions and post-processing activities. In PORT, all analysis models and IERS (International Earth Rotation and Reference Systems Service) conventions recommended by the IVS for routine VLBI single session processing are implemented. The GFZ Combination and VLBI group analyzed and contributed 568 S/X and 100 VGOS sessions (solution code “gfz2022a”) for the 2023 update, as well as 180 S/X and 96 VGOS sessions (solution code “gfz2024a”) for the 2024 update of the ITRF2020 in the reporting period. Software development within the last two years focused on the design and implementation of an SQLite database system that drives session handling within the operational system. PORT is open-source under the terms of the GNU General Public License and available for download from GFZ’s GitLab server.

VLBI simulation studies are carried out to assess the impact on geodetic parameters when a new antenna is added to the existing ground network. In Dhar et al. (2023) [3], we analyzed present and future VLBI networks to identify favorable locations for a new antenna on the Indian subcontinent. The strategy involved optimized scheduling, Monte Carlo simulations, and analysis for investigating the improvement in estimated geodetic parameters, such as Earth Orientation Parameters (EOP) and TRF (terrestrial reference frame). To ensure a realistic outcome from the VLBI simulations, local environmental conditions affecting VLBI operations and sustainability were incorporated using a weighted scoring method. This informed decision making of selecting suitable sites for VLBI establishment is substantial for supporting the well-known GGOS (Global Geodetic Observing System) 2020 goals (Gross et al. 2009) [7] of the IAG (International Association of Geodesy).

VLBI portrays strong potential for satellite orbit determination and can complement established space geodetic techniques, such as SLR. Dhar et al. (2024a) [4] highlighted the significance of India’s geodetic and astrometric VLBI initiative as of Project “Saptarishi.” The study demonstrated the role of VLBI in NavIC satellite orbit determination, enhancing precision of EOP and station coordinates to ensure a precise TRF, and improving the CRF through better observation of southern hemisphere radio sources. The findings from the study laid a solid foundation for endorsing the establishment of VLBI antennas in India.

Many applications such as navigation, astronomy, space exploration, climate studies, timekeeping, disaster monitoring, and geodynamic studies all rely on predictions of EOP. With machine learning techniques, the prediction of complex and data extensive patterns has become simpler and reliable. In Dhar et al. (2024b) [5] we developed a robust short-term prediction model based on Gaussian Process Regression (GPR) for improving UT1–UTC and LOD (length of day) predictions. The optimal configuration of the GPR kernel and its hyperparameters, defined over a complex search space involving both continuous and discrete variables, was determined using Genetic Algorithm (GA) within the prediction model, resulting in improved accuracy for EOP forecasts. The study conducted a series of experiments using various forecasting techniques and EOP products (IERS EOP 20 C04, USNO Finals, JTRF2020, DTRF2020) in both hindcast and operational settings to evaluate the most effective prediction approach. Our EOP prediction quality was performing comparably to some of the best available methods contributed to the IERS 2^{nd} Prediction Comparison Campaign [22, 23]. In Dhar (2024c) [6], the impact of climate was extensively investigated in the seasonal timescales of LOD for developing an improved long-term prediction model.

In the project AGORA (Alignment of Gaia optical and radio reference frames) funded by the German research foundation (DFG), we worked on the highly precise alignment of the Gaia data products through VLBI data analysis by delivering a state-of-the-art and consistent realization of ICRS based on VLBI data during the entire duration of the satellite mission (07/2014 to 01/2025). To achieve this goal, data obtained by IVS and partner organizations, such as the VLBA (Very Long Baseline Array), are utilized. One scientific objective of the project is the combination of the VLBI observations at the various IEEE-bands into a consistent set of celestial reference frames. Many active galactic nuclei (AGN) and their optical counterparts, typically the core of the mother galaxy or one or several bright components of the jet, are included in the Gaia data products as well as in ICRS realizations. Hence, these objects can be used as pass points for the alignment. Optical counterparts of AGN, however, are extremely faint, and, accordingly, this approach works only for the faint fraction of the Gaia objects. For this reason, we conducted observations of radio stars in project AGORA in order to align the bright fraction of Gaia objects as well. Radio stars can be relatively bright in optical wavelengths; in radio wavelengths, however, they are typically extremely faint. Interim results of the project were published by Lunz et al. (2023, 2024) [12, 13].

In the DFG-funded project NextGNSS4GGOS (Next generation GNSS constellations for GGOS-compliant geodetic solutions), simulations of innovative observation types have been performed using the EPOS-OC software (Neumayer et al. 2024 [15]) to assess their impact on satellite orbits, global reference frames, and Earth orientation parameters. The potential of VLBI transmitters is studied in Raut et al. (2023) [17] and of accelerometers in Schreiner et al. (2024) [20]. The full list of project-related publications can be found on the corresponding webpage. During 2023–2024, S. Raut was working at GFZ as a research assistant in the project NextGNSS4GGOS. Until 11/2024 he conducted studies as a PhD student at TU Berlin towards his thesis entitled "Innovative observation types in next-generation GNSS." His main area of research was the evaluation of the prospects of placing VLBI transmitters on next-generation Galileo satellites in a simulated environment. He assessed impacts on Earth orientation parameters and global reference frames [17, 18]. Additional prospects included estimation of Geocenter coordinates, precise orbit determination, and low-degree gravity field coefficients from VLBI observations of satellites [19]. Furthermore, a combination of VLBI and GNSS techniques using a space tie at the common satellite was achieved enabling the UT1–UTC information to be transferred from VLBI to GNSS directly.

Simulation studies of a GRASP-like co-location in space mission were conducted by Pollet et al. (2023) [16]. Several of the GFZ colleagues are also co-authors of the White Paper of the planned ESA mission Genesis (Delva et al., 2023 [2]).

N. Mammadaliyev stayed at GFZ/TU Berlin until 04/2023. His research focused on the co-location of the main space geodetic techniques in space to realize a global Terrestrial Reference System. In the frame of his PhD thesis, entitled "Co-location of space geodetic techniques in space" [14], he investigated precise orbit determination of satellites using VLBI observations, the combination of VLBI and SLR through space ties, and the impact of different error sources on the final TRF in terms of simulations.

A research project under the name "Combination of Space Geodetic Techniques with Clock Ties and Atmospheric Ties (COCAT)" was funded by DFG within the research unit "Clock Metrology." The primarily involved scientists are J. Wang, K. Balidakis, and H. Schuh. In the project, they investigate how the inter-technique combination of estimates of atmospheric delay coefficients and parameters that describe variations in frequency standards affects multi-technique reference frames. The work builds on developments carried out in Wang (2021) [24] where VLBI and GNSS are combined at the observation equation level. The scientific objectives of COCAT are to challenge the state-of-the-art regarding (i) modelling weather-induced loading and refraction effects; (ii) combining atmospheric delay coefficients; (iii) combining clock parameters; and (iv) performing the inter-technique combinations at the observation equation level.

In the framework of the ITRS 2020 realizations, J. Wang investigated the behavior of the VLBI scale. It was confirmed that the VLBI scale exhibits a drift after about 2013 (Wang et al. 2023) [25], which is visible in ITRF2020 and JTRF2020, but not in DTRF2020. The problem was identified to be related to mismodeling of surface deformation at station NYALES20. Nevertheless, the non-linearities at this site could not fully explain the observed drift of scale.

GNSS and SLR data were analyzed during CONT14 and CONT17. The normal equation systems featuring station coordinates, polar motion, LOD, and geocenter coordinates, as well as zenith delays and gradients, were combined with VLBI NEQs analyzed consistently employing GFZ's software PORT. In addition to applying local (station positions) and global (Earth rotation and geocenter) ties during the combination, atmospheric ties were applied as well to constrain the relative variation of atmospheric delay coefficients at co-location sites. Balidakis et al. (2023) [1] highlighted that such a combination is only possible with consistent modeling and parameterization across space-geodetic techniques and that the success of the combination depends on the atmospheric tie weighting and the treatment of the artificial delay biases at co-located stations.

To explore the potential of atmospheric ties being used in addition to local/global/space ties in the multi-technique combination, the IAG Joint Working Group (JWG) 1.3 "Intra- and Inter-Technique Atmospheric Ties", established by R. Heinkelmann in 2015, was carried on during the 2019–2023 IAG term by K. Balidakis and D. Thaller (BKG).

C. Kitpracha completed his doctoral studies at Technische Universität Berlin and was a guest researcher at the Combination and VLBI group at GFZ, supported by a DAAD scholarship until 2023. His research primarily focused on tropospheric effects in space geodetic techniques and on the improvement of combination methods based on tropospheric ties, particularly for GNSS and VLBI. In his doctoral thesis entitled "The Improvement of VLBI Tropospheric Modeling with a Dense GNSS Network" [9], he investigated systematic effects of tropospheric parameters in intra- and inter-technique combinations. In the thesis, he demonstrated that the presence of instrumental biases limits the combination of VLBI and GNSS tropospheric parameters. Furthermore, he presented an approach to improving the GNSS–VLBI combination by applying tropospheric ties with instrumental corrections. The results were also presented in Kitpracha et al. (2022) [8]. Together with R. Heinkelmann, C. Kitpracha works on the K-band VLBI solution of GFZ applying PORT for K-band VLBI analysis. After completing his doctoral studies in 2024, C. Kitpracha returned to the Department of Survey Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand, where he continues his research on tropospheric parameters and K-band VLBI, while remaining affiliated with the GFZ Combination and VLBI group as a guest member.

P. Küreç Nehbit has been a guest of the Combination and VLBI group from 09/2019 to 09/2020. The title of her study, which was granted by The Scientific and Technological Research Council of Turkey (TUBITAK), was "Joint Evaluation of VLBI and GNSS Observations with the Sensitivity and Robustness Analyses." In the following, P. Küreç Nehbit published several articles also with us [10]. In 2023, her latest article with us (Küreç Nehbit et al. 2023 [11]) was about the sensitivity levels when combining GNSS and VLBI. The effect of the selection of co-location sites in the inter-technique combination was investigated applying different scenarios. In this study, it was found that the selection of the co-location sites and their standard deviations are important properties for the network quality.

P. Poopat was at GFZ during his M.Sc. studies (2023–2024) in Geodesy and Geoinformation Science at Technische Universität Berlin. Work on his thesis, entitled "The Role of Cable Calibration for Geodetic VLBI Analyses," started in 09/2024. Therein, he investigates cable calibration inconsistencies in VLBI analysis and their impact on clock and geodetic parameters using PORT. He intends to develop correction methods for discontinuities demonstrating improvements.

E. Tamaryan, M.Sc. student at TU Berlin, investigated whether the time-consuming quality control task for cable delay corrections in VLBI data analysis could be automated. In 2023–2024 he worked towards his MSc thesis entitled "Modeling Cable Calibration Data in the Analysis of VLBI Observations." Therein, he proposed an algorithm of analytical modeling within an information-theoretic framework to capture cable-induced VLBI signal delays caused by environmental factors and mechanical bending of the 5-MHz reference cables during VLBI antenna slewing.

3 Current Status and Future Plans

As already mentioned, PORT is routinely developed for the timely processing of VLBI sessions and post-processing activities. Future plans include code refactoring and improved modularization. Additional development resources will be devoted to improve the PORT installation and its documentation.

We intend to take part in future ITRS realizations in terms of reprocessing efforts and updates, such as the ITRF2020-u2023 and ITRF2020-u2024. In the framework of the IAU WG ICRF4, development will focus on the global module of PORT in support of the ICRF4 related work and of the work within project AGORA.

Further efforts are planned at the Combination and VLBI group of GFZ to improve the analysis of VLBI observations of satellites.

Members of the GFZ Combination and VLBI group plan to start new efforts in integrating ring laser, LLR, and VLBI as part of a project in the potential DFG research unit RING.

Acknowledgements

Part of the work described in this report is supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) within the projects NextGNSS4GGOS (Next generation GNSS constellations for GGOS-compliant geodetic solutions, grant number GL 1028/1-1), AGORA (Alignment of Gaia optical and radio reference frames), and Combination of Space Geodetic Techniques with Clock Ties and Atmospheric Ties (COCAT) within the research unit Clock Metrology, which is acknowledged very much.

We kindly acknowledge the funding received by The Scientific and Technological Research Council of

Turkey (TUBITAK) and the German Academic Exchange Service (Deutscher Akademischer Austauschdienst, DAAD).

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