GFZ Analysis Center 2021–2022 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, planned future work is outlined.

1 General Information

The Helmholtz Centre Potsdam, GFZ German Research 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 "Geodetic and astrometric VLBI," led by Robert Heinkelmann, was established in late 2012. The VLBI group is an Associate Analysis Center (AC) of IVS. Within department 1 it closely co-operates with the recently formed Working Group "Combination of Space Geodetic Techniques" led by Susanne Glaser.

2 Activities during the Past Two Years

Within our activities of supporting ITRF realizations, we analyzed all (6,516 X/S and 38 VGOS) sessions listed by the IVS for inclusion in ITRF2020, utilizing GFZ's analysis software tool PORT, the Potsdam Open Source Radio Interferometry Tool [16]. Based on the single-band correlation quality codes, selected ionosphere-free multi-band group delays were calculated, employing information nested within the—at the time of analysis—latest version of the vgosDB dataset produced by GSFC. An independent analysis was carried out for the identification of clock breaks (both true and apparent mainly due to erroneous cable-cal, phase-cal, or in situ barometer records), set-up of baseline offsets, re-weighting of observations in a baseline-, station-, and AGN-dependent manner, identification of observations that do not agree with the deterministic and stochastic models adopted (outliers), as well as selection of stations and AGN that participated in the datum definition. Our SINEX includes two normal equation systems featuring station and AGN coordinates as well as the full set of EOP and ERP rates, where the displacement effects of non-tidal atmospheric load-

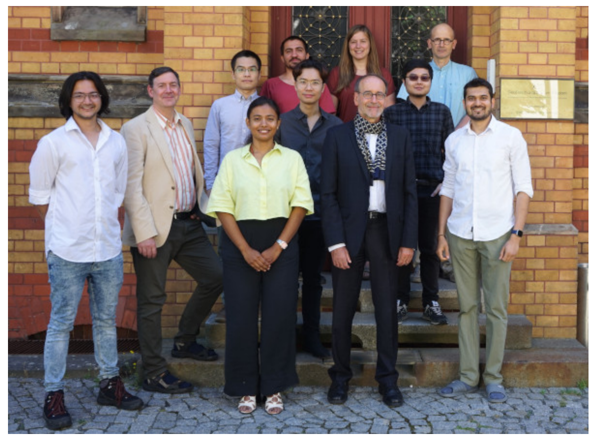

Fig. 1 Members of the GFZ Working Groups "Geodetic and astrometric VLBI" and "Combination of Space Geodetic Techniques" in June 2022. (S. Glaser not pictured in the photograph.)

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ing were or were not mitigated, employing in-house models developed at the GFZ. New models were implemented for pole tidal loading, galactic aberration, antenna gravitational deformation, and high-frequency Earth rotation variations. For stations with poor observation geometry the set-up of piece-wise linear parameters, such as atmospheric delay and clock coefficients, was modified, in order to reduce the impact of the stochastic constraints adopted. Our contribution to ITRF2020 (solution code 'gfz2020b') is publicly available in SINEX format.

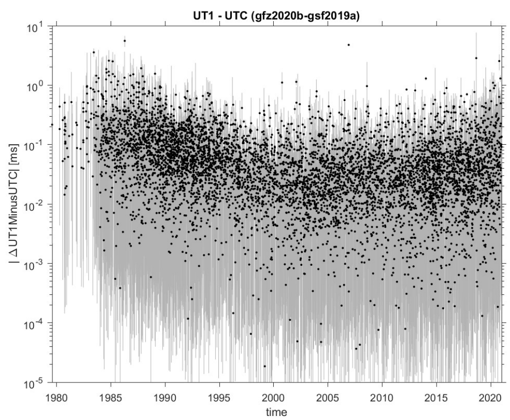

Fig. 2 Comparison of two estimates of UT1–UTC, one derived from GFZ's contribution to ITRF2020 ('gfz2020b'), the other extracted from GSFC's data set ('gsf2019a'). The black dots mark the modulus of the difference, the uncertainties of the difference are plotted as grey lines.

Based on actual VGOS observations, we demonstrated that the instrumental noise level in VGOS observations is only about 2 ps, one order of magnitude better than that in the typical legacy observations, and the effects of source structure are on average about 20 ps [21].

Xu et al. (2021b) [22] have, for the first time, successfully derived high-quality structure maps from VGOS observations through a technique of closure imaging that overcomes the problem of missing antenna calibration information. The closure imaging is now done routinely for VGOS observations through pipelines. The effects of source structure in VGOS observations are better understood through these maps.

A simulation study, performed to investigate the impacts of image alignment over frequency for VGOS and new methods, including ones using phase delays, were developed to solve this problem [24]. The differences in radio source positions, estimated from VLBI observations and measured by Gaia, are investigated and radio source structure is found to be one of the major factors contributing to these differences [23].

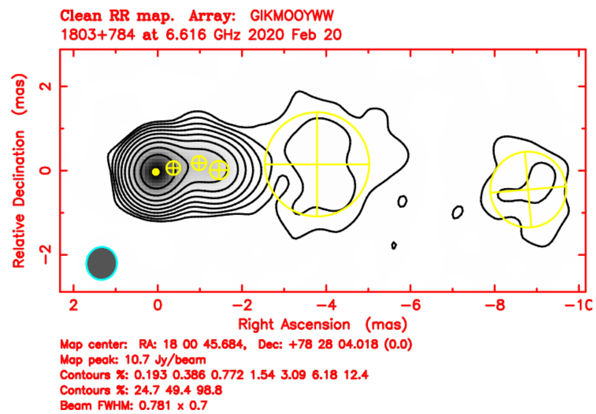

Fig. 3 Image of source structure for source 1803+784 at 6.6 GHz that was obtained from VGOS session VO0051 (20 Feb 2020). The six Gaussian components shown as yellow ellipses were determined by model fitting in DIFMAP.

Baseline vector repeatability at the sub-mm level was obtained based on an analysis of phase delays of the very short baseline WETTZ13N–WETTZELL from 93 experiments of the legacy VLBI, as shown in Figure 4 [25].

An important part of GFZ's research activities focuses on the exploitation of VLBI observations for comparison and external validation with other space geodetic techniques. In Männel et al. (2021) [11], zenith total delays (ZTDs) from VLBI data analyses at the stations NYALES20 and NYALE13S were used for comparison to GNSS during the MOSAiC expedition. Overall, there is a good agreement between the ZTDs from VLBI and those derived from GNSS observations aboard RV "Polarstern" and at the IGS station NYA2.

Simulations and combinations of all four space-geodetic techniques, including VLBI, to a space-tie satellite were performed within the project GGOS-SIM-2 ("Simulation of the Global Geodetic Observing System"), funded by the German Research Foundation. All techniques were combined via co-location in space for six different space-tie satellite scenarios [15]. VLBI observations of satellites carrying VLBI transmitter

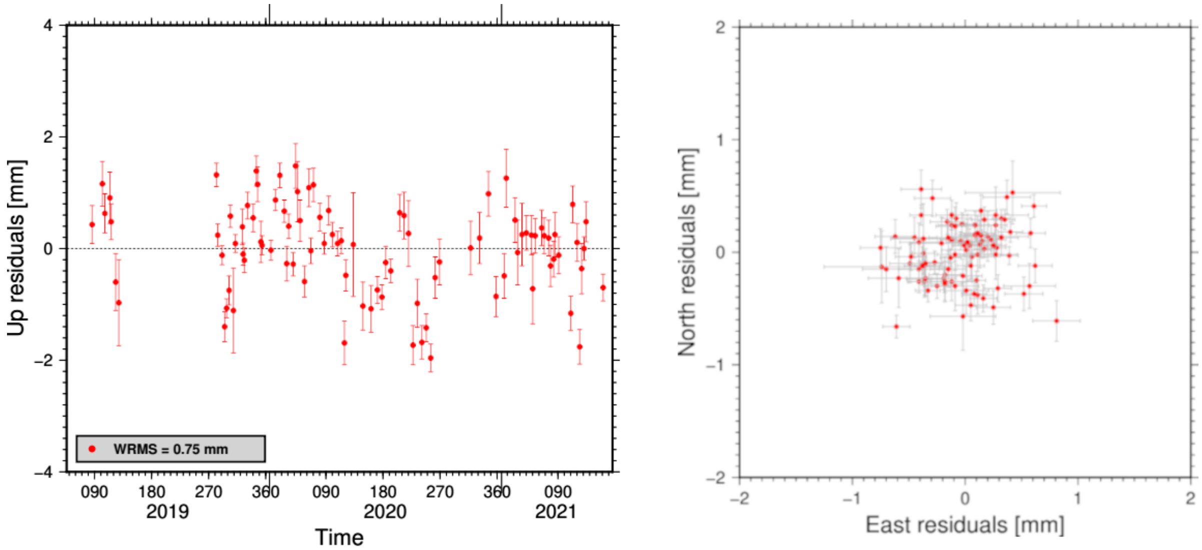

Fig. 4 Residuals of the estimated coordinates of antenna WETTZ13N from phase delays of the baseline WETTZ13N–WETTZELL in 93 VLBI experiments [25]. Left: up component. Right: north component vs. east component.

payloads allow to access the geocenter of the Earth [10]. We also contributed to the co-location in space satellite proposal GENESIS, which recently was approved by ESA [1, 6, 7]. In the framework of the DFG-funded project NextGNSS4GGOS, a VLBI transmitter as a new type of observation for next-generation GNSS satellites was simulated [14].

For the purpose of realizing consistent TRF, CRF, and EOP, we implemented the multi-technique integrated processing modules in the Positioning And Navigation Data Analyst (PANDA) platform, which can now process GNSS, VLBI, and SLR observations [17]. Based on the platform, we demonstrated that applying tropospheric ties improves the VLBI network stability and EOP estimates in CONT05–CONT17 sessions [18]. We also demonstrated that UT1–UTC estimates in the Intensive sessions are improved by tropospheric ties [19]. Moreover, the determination of CRF also benefits from the integrated GNSS and VLBI solutions [20].

To explore the potential of atmospheric ties being used in addition to local/global/space ties in the multi-technique combination, an IAG Joint Working Group (JWG 1.3) was established by R. Heinkelmann in 2015. In the current IAG term (2019–2023) K. Balidakis and D. Thaller (BKG) have taken over the responsibility for the JWG “Intra- and Inter-Technique Atmospheric Ties.”

At GFZ we have studied the intra- and inter-technique differences mainly induced by varying frequency, position, and the observing system. By employing simulated observations we performed a multi-technique combination, utilizing NWM-derived atmospheric ties. The benefit of estimating common tropospheric parameters for co-located VLBI radio telescopes utilizing atmospheric ties was explored by Kitpracha et al. (2022a) [8]. The study demonstrates the potential of using atmospheric ties in aiding a datum transfer between two VLBI parallel networks during CONT17. The impact of tropospheric tie models and instrumental biases on atmospheric ties was investigated in Kitpracha et al. (2022b) [9]. This study conducted a dedicated GNSS co-location site experiment using various GNSS antennas to investigate instrumental biases and it proposed a calibration method.

In order to fulfill operational and scientific user requirements on low-latency information of Earth’s orientation in space, we have investigated and used machine learning (ML) algorithms to predict the EOP. These algorithms make data driven predictions based on pattern recognition and computation learning on the data. The ML algorithms were combined with the filter-based approach to capture the stochastic seasonal behavior of EOP time series. The geophysical phenomenon correlated to EOP were also incorporated in the prediction algorithm for a better and robust prediction [3, 4].

During the reporting period simulation studies were used to obtain empirical results about the performance of new VLBI stations and observation strategies in India. Specifically, the impact on the geodetic parameters, such as EOP, TRF coordinates, and CRF coordinates, were studied. These geodetic parameters are estimated from the simulated VLBI observations that are generated using scheduling, simulation, and analysis. Then, the results are compared for studying the impact of the new strategy. The primary metric of comparison is the mean formal error or baseline length repeatability. We used this technique to study the favorable locations for the addition of new VGOS antennas in India. The impact of additional antennas was studied with respect to the current and future IVS networks for a comprehensive assessment. To make the assessment more realistic, local environmental conditions of the new antenna locations were also incorporated in the study. These environmental conditions were considered based on their effect on the quantity and quality of the VLBI observations. For this, a weighted scoring model was developed with the scores and weights based on the probable impact and occurrence frequency of disrupting environmental factors, respectively. This approach will avoid the possibility of new VLBI antennas ending up in an unfavorable location and underperforming substantially in terms of the expected improvement of geodetic parameters as determined from the simulation study. Thus, it would help to mark the high performing favorable locations for the new VLBI establishment. The results show that VGOS antennas at favorable locations in India outperform other locations by a factor of 1.1 to 5.0 in improvement percentage of derived geodetic parameters [2, 5].

Finally, we investigated the influence of El Niño-Southern Oscillation (ENSO) on LOD using the Wavelet Coherence method for the three major El Niño events in 1982, 1997, and 2015. This method also provides phase information. For details see Raut et al. (2021) [12]. In addition, Raut et al. (2022a) [13] evaluated and compared dUT1 from various networks (e.g., VGOS, legacy S/X, and three different types of Intensive sessions) during the CONT17 campaign.

3 Current Status and Future Plans

In late 2022, project COCAT "Combination of Space Geodetic Observations with Clock Ties and Atmospheric Ties" (PI K. Balidakis, co-PI H. Schuh) was approved within the DFG research unit TIME (spokesperson Professor Ulrich Schreiber, TU Munich). Work within COCAT builds upon advances in numerical weather prediction as well as in precise timekeeping and synchronization between frequency standards realized by time coherence observables, and will be directed towards the combination of VLBI, GNSS, and SLR employing atmospheric and clock ties in addition to local and global ties, at the observation equation level within a single software package. Within the same DFG research unit the project "Novel clock technologies for combination on ground and in space: real data and simulation" (PIs are Manuela Seitz, DGFI-TUM and Susanne Glaser, GFZ) also received funding approval and will investigate the impact of a common clock and a common reference point on the combined solution, the global terrestrial reference frame.

A European Research Council (ERC) starting grant has been awarded to Minghui Xu. The project is called "Astrogeodesy." It aims to develop a new data processing strategy for VGOS and will investigate source structure effects. A new group will be established at the GFZ in 2023 with the support of this project.

As already mentioned, PORT is GFZ's VLBI analysis software package and is routinely employed for the timely processing of VLBI sessions and post-processing activities. The estimation procedures take into account all relevant data analysis models and conventions that are recommended by the IVS for routine VLBI single-session processing. PORT constitutes a framework for research and development activities within the VLBI Working Group and is part of the tool set employed in educating young researchers at GFZ. The current source base is open-source, licensed under the terms of the GNU General Public License and available for download from GFZ's GitLab server. Future plans include code refactoring efforts to clarify procedure interfaces, improve modularization and readability, as well as support for Microsoft Windows® and MacOS® operating systems. Additional development resources will be devoted to improving the PORT installation and its documentation.

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