GFZ Analysis Center 2019–2020 Report

Robert Heinkelmann[1], Susanne Glaser[1], Georg Beyerle[1], Harald Schuh[1,2], James Michael Anderson[2,1], Kyriakos Balidakis[1], Sujata Dhar[1], Okky Syahputra Jenie[1,2], Chaiyaporn Kitpracha[1,2], Susanne Lunz[1,2], Nicat Mammadaliyev[2,1], Sadegh Modiri[1,2], Shrishail Subash Raut[1,2], Jungang Wang[2,1]

Abstract This report provides general information and a component description of the IVS Analysis Center at GFZ. Current activities and recent results are mentioned, and the 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. At this research facility, within Department 1 "Geodesy" and Section 1.1 "Space Geodetic Techniques," a VLBI group has been established at the end of 2012. This group is an Associate Analysis Center (AC) of IVS.

2 Component Description

GFZ is an Associate AC of the IVS. We have installed and partly automatized our VLBI analysis process in preparation for becoming an Operational AC. We are also supporting a combination center for tropospheric products.

---

1. Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences
2. Technische Universität Berlin KAI 2-2, Department of Geodesy and Geoinformation Science, Chair of Satellite Geodesy

GFZ Analysis Center

3 Staff

Since the 2017–2018 Biennial Report, Suxia Gong has left the VLBI group to join the Local Environment Management and Analysis Department of University of Liège, Belgium. We wish her the best of luck in her future career. Minghui Xu is now a Research Fellow with the Department of Electronics and Nano-engineering of Aalto University, Finland, and works in a project of Tuomas Savolainen entitled 'NT-VGOS: From quasars to geodesy: how astronomy can enable a new era in ultra-precise geodetic measurements.' He is still closely related to us and to our work through his role as Mercator Fellow (DFG) in our project 'ECO-RAS: extension of the coordinate parameterization of radio sources observed by VLBI.' Kyriakos Balidakis and Sadegh Modiri have successfully defended their PhD theses [1, 23]. In 2019 Csilla Fodor [6], Eötvös Loránd University, Faculty of Science, Geophysics, Budapest, Hungary and in 2020 Pakize Küreç Nehbit [13], Department of Geomatics Engineering, Kocaeli University, Turkey, kindly visited our group as guests. Additionally, we have had the pleasure of welcoming the following new colleagues to our group, all of which will be pursuing a PhD (in alphabetical order):

- Sujata Dhar, B.Tech (Hons) degree from NIT Raipur and PMRF from IIT Kanpur, India, is investigating the Earth Orientation Parameters from VLBI and GNSS and does simulations and combinations of space geodetic techniques.
- Shrishail Subhash Raut from India, M.Eng Space Engineering of TU Berlin, works on the improvement of Earth Orientation Parameters by combining VLBI and GNSS.

- Jungang Wang, ME Geodesy and Surveying Engineering from Tongji University, Shanghai, China, works on Integrated Processing of GNSS and VLBI on the observation level.

The current members of the VLBI group and their main topics are listed in Table 1, and a picture of us is presented in Figure 1.

4 Current Status and Activities

VLBI Data Analysis Software Development
The VLBI group at GFZ Potsdam employs the Potsdam Open Source Radio Interferometry Tool (PORT) for data processing and analysis. The MATLAB source code of PORT was originally based on the Vienna VLBI Software (VieVS). Since 2012 PORT development at GFZ is directed towards operational data processing in support of GFZ's IVS activities as well as implementation of alternative analysis algorithms, such as parameter estimation using Kalman filtering. Within the last years, efforts were directed at re-factoring tasks to improve code efficiency and to implement modularity. The code is going to be open source and will be made available via GFZ's source code repository, once the first stable public release version is ready.

ITRF2020 Contribution
The GFZ VLBI group delivered input to the current International Terrestrial Reference Frame (ITRF2020) call, employing PORT. Our contribution consists of 6,552 SINEX featuring estimates for station and AGN coordinates, and EOP and the rates thereof, as well as the related datum-free normal equation systems. The vast majority of the sessions analyzed have S-/X-Band observations, and a few VGOS sessions were analyzed as well. While the effect of non-tidal atmospheric loading was taken into account adopting GFZ's models, its impact on the solution may be removed by means provided within the SINEX (calibration blocks). To accommodate the latter as well as other special considerations for ITRF2020, PORT has been enhanced accordingly (e.g., gravitational telescope deformation modeling [25] and handling of poorly observed AGN). The baseline length repeatability of our solution decays as a function of baseline length x following $\sqrt{(5.4 \pm 1.3)^2 + ((0.0027 \pm 0.0002)x)^2}$.

Reference Frame Simulations towards GGOS
GGOS-SIM[1]: Simulation of the Global Geodetic Observing System is a joint project of TU Berlin and GFZ Section 1.2 situated in Oberpfaffenhofen near Munich, Germany. It is funded by the German Research Foundation (DFG, SCHU 1103/8-2). Therein, we simulate the four space geodetic techniques (GNSS, SLR, DORIS, and VLBI) currently contributing to the ITRF and investigate the impact of different local tie scenarios on the combined frame of GPS, SLR, and VLBI [8]. Furthermore, we simulated the future network development of SLR in combination with GPS and VLBI [7]. In the second phase of GGOS-SIM that started on January 1, 2019, we focus on simulations of co-location in space involving the four space geodetic techniques [18]. In the project ADVANTAGE funded by the Helmholtz Gemeinschaft the impact of a future GNSS constellation "Kepler" on geodetic parameters also within the combination with VLBI [9] is investigated with simulations.

Gaia–VLBI
The optical astrometric satellite mission Gaia (ESA) is providing positions and proper motions of hundreds of thousands of quasars at a level of precision comparable to or even better than the current ICRF3 position accuracies. In the research project ECORAS funded by the DFG (HE 5937/2-2, SCHU 1103/7-2) the comparison of the Gaia and VLBI celestial coordinates is being exploited to determine systematic, possibly technique-dependent, reference frame effects [14]. We paid particular attention to the analysis of the misalignment of the Gaia bright reference frame, which we enhanced by homogenizing and extending the VLBI data [15, 16]. As part of the efforts to improve the alignment of the radio and optical frames and the agreement of the positions of individual sources, we have studied the detection, modeling, and correction of radio source structure effects on celestial coordinates and observables [27, 28]. In addition, we are investigating effects such as core shift that potentially induce frequency-dependent position variations, as well as apparent proper motions induced by the evolution of intrinsic source structure.

---

[1] https://www.earth.tu-berlin.de/menue/forschung/laufende_projekte/ggos_sim/parameter/en/

Table 1 Current members of the VLBI group at GFZ including one MSc student.

Name	Main activity / function
Harald Schuh	Director of Department 1 and Head of Section 1.1 of GFZ
Robert Heinkelmann	Head of VLBI group
Sadegh Modiri	Prediction and geophysical effects of EOP
Susanne Glaser	Combination and simulation of space geodetic techniques, projects: GGOS-SIM, ADVANTAGE
Jungang Wang	Combination on the observation level
Shrishail Raut	Combination of GNSS and VLBI for EOP determination
Georg Beyerle	PORT development, project: ADVANTAGE
Fikri Bamahry	MSc student, climate signals obtained from VLBI data analysis
Chaiyaporn Kitpracha	Combination of GNSS and VLBI tropospheric parameters and atmospheric ties
Kyriakos Balidakis	Atmospheric and geophysical effects, PORT development
Nicat Mammadaliyev	Co-location in space, project: GGOS-SIM
Susanne Lunz	Gaia–VLBI, project: ECORAS
Sujata Dhar	Real-time prediction of EOP, simulations
James Anderson	Source structure, project: ECORAS, PORT development, EU-VGOS
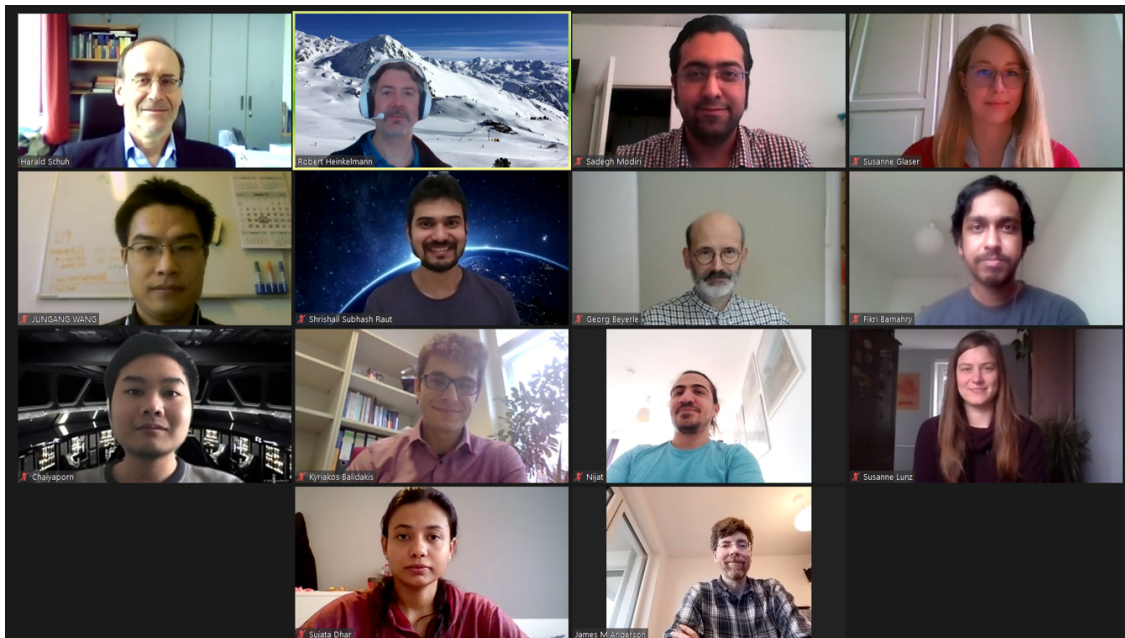
Fig. 1 A screenshot of the GFZ VLBI group during a meeting on January 22, 2021. The names given in Table 1 are ordered from top left to bottom right.

Geophysical Loading Effects

Transient mass redistribution within Earth's fluid envelope (atmosphere, oceans, and continental water storage) displaces VLBI stations at the cm-level at a large frequency spectrum. We develop consistent models for these effects and provide them operationally.[2] A study assessing these models in the analysis of VLBI and GNSS observations has been carried out [17].

---

[2] http://rz-vm115.gfz-potsdam.de:8080/repository

Atmospheric Refraction Effects, Ties and Modeling, Climatological Studies

In addition to an appropriate parameter set-up in the geodetic adjustment, advanced atmospheric delay modeling is necessary to improve the accuracy of geodetic products. Employing the in-house ray-tracing software and state-of-the-art NWMs such as ERA5 (31 km) and ECMWF's operational model (9 km), we have worked on the development of accurate ray-traced delays, mapping functions, and non-linear

asymmetric delay models and assessment thereof in VLBI data analysis. We have also investigated the improvement from employing water vapor radiometer data in VLBI data analysis. Starting from 2019, we make publicly available[3] atmospheric delays from an ECMWF operational analysis (9 km) and ERA5 since 1979.

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 has taken over the organization of the JWG together with D. Thaller (BKG). To summarize activities related to "Intra- and Inter-Technique Atmospheric Ties", a Web page has been set up.[4] At GFZ, we have studied the intra- and inter-technique differences mainly induced by varying frequency, position, and observing system [e.g., 2]. Employing simulated observations we can perform the multi-technique combination utilizing NWM-derived atmospheric ties, to the advantage of the combined solution. The combination of real VLBI and GNSS data at the observation equation level employing atmospheric ties has been explored in the PhD thesis of J. Wang that will be defended in 2021. To predict zenith wet delays, we have utilized machine learning techniques, in particular long-short term memory and a combination of singular spectrum analysis (SSA) and copula. We have obtained promising results for tropospheric delay prediction at Wettzell, but this approach needs to be refined further to achieve geodetic accuracies.

We have continued studying long-term integrated water vapor variations estimated from VLBI, GNSS, and state-of-the-art weather models, such as ERA5. The spatio-temporal evolution has been continued in the framework of the MSc thesis of Fikri Bamahry.

IVS Tropospheric Combination
The algorithm for the IVS tropospheric combination was revised making it more robust. Several changes are in progress, including the epochs at which the tropospheric products are reported (from HH:00 to HH:30) and the combination of gradients. As too few IVS Analysis Centers currently contribute to

this product, the combination is on hold and will be reactivated once the submissions become available. Following the expression of interest on behalf of IGS and EUREF, we look forward to more Analysis Centers contributing to the product.

Earth Orientation Parameters
The GFZ VLBI group continued its activities to improve Earth Orientation Parameter theories and models in cooperation with other institutes and universities. We studied several minor effects on Earth rotation, derived from geophysical properties not considered so far [21, 6]. We have investigated how to improve the estimation of daily and sub-daily ERP from CONT17 data [24]. Together with the University of Alicante, Spain, we developed some studies on the revision and improvement of Earth rotation theories and models' accuracy and consistency [4, 5].

Moreover, we proposed a novel hybrid approach to predict EOP. A stochastic method called copula combined with singular spectrum analysis (SSA) was introduced for EOP prediction [19]. We analyzed the potential of copula-based methods for predicting Earth rotation parameters derived from the combination of different satellite geodetic sensors and other geophysical parameters, such as effective angular momentum functions [22]. Our new hybrid method is competitive with the existing ones and even better than many of them depending on the EOP and the prediction length, taking into account the final design of the procedures. Our method was also applied to predict other geophysical parameters.

Another challenging task was investigating the interconnection between the celestial pole motion (CPM) and geomagnetic core field (GMF) in order to improve the current CPM prediction methods. We use the CPM time series obtained from VLBI observations and the latest GMF model to explore the correlation between CPM and the GMF [20]. Our preliminary results reveal significant common features in the CPM and GMF variations, which show the potential to improve our understanding of the GMF's contribution to Earth rotation [23].

European VGOS
In an effort to learn how to utilize and improve geodetic VLBI using VGOS, many groups within Europe formed the European VGOS (EU-VGOS) project to investigate how VGOS results could be improved

---

[3] ftp://ftp.gfz-potsdam.de/pub/home/kg/kyriakos/internal/PMF/

[4] https://www.gfz-potsdam.de/en/section/space-geodetic-techniques/projects/iag-jwg-atmospheric-ties/

through changes in scheduling, correlating, calibrating, fringe-finding, correcting for source structure, and various other areas. Initially starting with observations at three European VGOS sites, EU-VGOS test sessions have since incorporated the Ishioka VGOS station as well. The GFZ has been involved in the EU-VGOS project since its inception.

5 Future Plans

In addition to continuing to improve VLBI data analysis by better understanding systematic and random effects, the following activities are planned for 2021–2022: (i) development of PORT source code towards the first public release of the open access source code and beyond, (ii) automation of VLBI data analysis based on the vgosDb format, and (iii) working on GNSS–VLBI combination.

Acknowledgements

References

[1] K. Balidakis. On the development and impact of propagation delay and geophysical loading on space geodetic technique data analysis. *PhD thesis, TU Berlin*, 2019.

[2] K. Balidakis, S. Glaser, F. Zus, T. Nilsson, H. Schuh, and R, Gross. On the multi-technique combination with atmospheric ties. *EGU General Assembly Conference Abstracts*, 7818, 2020.

[3] S. Dhar, B. Nagarajan, and O. Dikshit. Estimation of Earth Rotation Parameters for Enhancing the Precise Realization of ITRF. *EGU General Assembly Conference Abstracts*, 1594, 2019.

[4] J.M. Ferrándiz, D. Al Koudsi, A. Escapa, S. Belda, S. Modiri, R. Heinkelmann, and H. Schuh. A first assessment of the corrections for the consistency of the IAU2000 and IAU2006 precession-nutation models. *IAG Symposia*, doi `10.1007/1345_2020_90`, 2020.

[5] J.M. Ferrándiz, S. Modiri, S. Belda, M. Barkin, M Bloßfeld, R. Heinkelmann, and H. Schuh. Drift of the Earth's Principal Axes of Inertia from GRACE and Satellite Laser Ranging Data. *Remote Sensing*, 12(2), 2020.

[6] C. Fodor, R. Heinkelmann, S. Modiri, S. Raut, H. Schuh, and P. Varga. On the mutual interrelation between Earth rotation and earthquake activity. In C. Bizouard (ed.), *Proceedings of the Journées 2019 - Astrometry, Earth Rotation, and Reference Systems in the Gaia era*, pages 85–90, 2020.

[7] S. Glaser, R. König, K. H. Neumayer, K. Balidakis, and H. Schuh. Future SLR station networks in the framework of simulated multi-technique terrestrial reference frames. *J. Geod.*, 93, 2275–2291, 2019.

[8] S. Glaser, R. König, K. H. Neumayer, T. Nilsson, R. Heinkelmann, F. Flechtner, and H. Schuh. On the impact of local ties on the datum realization of global terrestrial reference frames. *J. Geod.*, 93, 655–667, 2019.

[9] S. Glaser, G. Michalak, R. König, B. Männel, and H. Schuh. Future GNSS Infrastructure for Improved Geodetic Reference Frames. *2020 European Navigation Conference (ENC 2020)*, doi: `10.23919/ENC48637.2020.9317460`, 2020.

[10] R. Heinkelmann, J. Anderson, K. Balidakis, S. Belda, G. Beyerle, S. Glaser, S. Gong, O. S. Jenie, M. Karbon, C. Kitpracha, S. Lunz, N. Mammadaliyev, S. Modiri, T. Nilsson, M. Xu, and H. Schuh. GFZ Analysis Center 2017/2018 Biennial Report. In K. L. Armstrong, K. D. Baver, and D. Behrend (eds.), *IVS 2017+2018 Biennial Report*, pages 199–203, NASA/TP-2020-219041, 2020.

[11] C. Kitpracha, S. Modiri, M. Asgarimehr, R. Heinkelmann, and H. Schuh. Machine learning based prediction of atmospheric zenith wet delay: a study using GNSS measurements in Wettzell and co-located VLBI observations.

EGU General Assembly Conference Abstracts, 4127, 2019.

[12] C. Kitpracha, T. Nilsson, K. Balidakis, S. Modiri, R. Heinkelmann, and H. Schuh. The impact of estimating common tropospheric parameters for co-located VLBI radio telescopes on geodetic parameters during CONT17. *J. Geod.*, submitted.

[13] P. Küreç Nehbit, R. Heinkelmann, H. Schuh, S. Glaser, S. Lunz, N. Mammadaliyev, K. Balidakis, H. Konak, and E. Tanır Kayıkçı. Evaluation of VLBI observations with sensitivity and robustness analyses. *Mathematics*, 8(6), pp. 939, 2020.

[14] S. Lunz, J. Anderson, R. Heinkelmann, M. Xu, S. Gong, and H. Schuh. Radio source position offsets among various radio frames and Gaia. Poster presented at the *24th Meeting of EVGA*, 2019.

[15] S. Lunz, R. Heinkelmann, J. Anderson, M. C. Johnson, A. Fey, and O. Titov. Gaia-VLBI: Phase-referencing continuum emission observations of optically bright stars with the VLBA (planned proposal). In C. Bizouard (ed.), *Proceedings of the Journées 2019 - Astrometry, Earth Rotation, and Reference Systems in the Gaia era*, pages 49–54, 2020.

[16] S. Lunz, J. Anderson, M. Xu, O. Titov, R. Heinkelmann, M. C. Johnson, and H. Schuh. Enhancing the link of the optically bright Gaia reference frame towards ICRS. *Astron. Astrophys.*, 2020/40266, submitted.

[17] B. Männel, H. Dobslaw, R. Dill, S. Glaser, K. Balidakis, M. Thomas, and H. Schuh. Correcting surface loading at the observation level: impact on global GNSS and VLBI station networks. *J. Geod.*, 93, 10, pages 2003–2017, 2019.

[18] N. Mammadaliyev, P. Schreiner, S. Glaser, K. H. Neumayer, R. König, R. Heinkelmann, and H. Schuh. Simulations of VLBI observations to satellites enabling co-location in space. *EGU General Assembly Conference Abstracts*, 20227, 2020.

[19] S. Modiri, S. Belda, R. Heinkelmann, M. Hoseini, J.M. Ferrándiz, and H. Schuh. EOP Can Save Human Life! How?. *EGU General Assembly Conference Abstracts*, 2019.

[20] S. Modiri, R. Heinkelmann, S. Belda, Z. Malkin, M. Hoseini, M. Korte, J.M. Ferrándiz, and H. Schuh. Interconnection of the celestial pole motion with the geomagnetic field. *International Union of Geodesy and Geophysics (IUGG) General Assembly*, Montreal, Canada, 2019.

[21] S. Modiri, R. Heinkelmann, S. Belda, Z. Malkin, M. Hoseini, M. Korte, J.M. Ferrándiz, and H. Schuh. On the correlation of Celestial Pole Offsets and geomagnetic field variations (recent achievements). Poster presented at *Journées 2019 - Astrometry, Earth Rotation, and Reference Systems in the GAIA era*, 2019.

[22] S. Modiri, S. Belda, M. Hoseini, R. Heinkelmann, J.M. Ferrándiz, and H. Schuh. A new hybrid method to improve the ultra-short-term prediction of LOD. *J. Geod.*, 94, 23, 2020.

[23] S. Modiri. On the improvement of Earth orientation parameters estimation using modern space geodetic techniques. *PhD thesis, TU Berlin*, 2021.

[24] S. Raut, R. Heinkelmann, S. Modiri, and H. Schuh. Effect of VLBI intensive sessions on daily and sub-daily ERP determined from CONT17 IVS data. In C. Bizouard (ed.), *Proceedings of the Journées 2019 - Astrometry, Earth Rotation, and Reference Systems in the Gaia era*, pages 141–145, 2020.

[25] S. Shoushtari, S. Glaser, K. Balidakis, R. Heinkelmann, J. Anderson, and H. Schuh. On the impact of gravitational deformation on VLBI-derived parameters. *EGU General Assembly Conference Abstracts*, 5100, 2020.

[26] J. Wang, K. Balidakis, M. Ge, R. Heinkelmann, and H. Schuh. GNSS and VLBI integrated processing at the observation level. *EGU General Assembly Conference Abstracts*, 5749, 2020.

[27] M. Xu, J. Anderson, R. Heinkelmann, S. Lunz, H. Schuh, and G. Wang. Structure Effects for 3417 Celestial Reference Frame Radio Sources. *The Astrophysical Journal Supplement Series*, 242, 5, 2019.

[28] M. Xu, S. Lunz, J. Anderson, T. Savolainen, N. Zubko, and H. Schuh. Evidence of the Gaia–VLBI position differences being related to radio source structure. *Astron. Astrophys.*, 2021.