BKG VLBI Analysis Center

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Abstract In 2023 and 2024, the activities of the BKG VLBI Analysis Center, as in previous years, consisted mainly of the routine VLBI analysis for IVS. Our solutions are computed with the geodetic VLBI software nuSolve [8] for the analysis of sessions in the vgosDb data format and the Calc/Solve software, release 2019.11.21, revision date 2020.01.23 [3]. In 2024 the generation of a BKG AC contribution for the first ITRF2020 update, i.e. labelled "ITRF2020-u2023", was completed. We are also supporting new software developments for the Bernese GNSS Software [1] in order to process VLBI data of the form vgosDb version 4.

1 General Information

The German Federal Agency for Cartography and Geodesy (BKG) maintains the VLBI Analysis Center with the status of an operational analysis center as defined by the International VLBI Service for Geodesy and Astrometry (IVS). The BKG VLBI Analysis Center is responsible for the computation of two types of Earth Orientation Parameter (EOP) series: first, the EOP-S time series derived from 24-hour sessions and, second, the EOP-I series derived from *Intensive* sessions. In addition to the EOP products, we provide session-wise SINEX files (SINEX = Solution INdependent EXchange format) for 24-hour as well as *Intensive* sessions. Furthermore, the VLBI group at BKG continues the regular submissions of the tropospheric parameter time series. The quarterly updated solutions were continued for providing terrestrial reference frame (TRF) and celestial reference frame (CRF) products. BKG is developing procedures to derive a VLBI-only EOP series by consistently combining 24-hour and *Intensive* sessions, ensuring a continuous EOP series with daily resolution [13]. Additionally, the BKG AC maintains an analysis workflow starting from the computed group delays in version 1 of the vgosDb wrapper file. The VGOS database processing chain for IVS product generation was further developed and refined during the reporting period. Technical VLBI data handling includes routine data acquisition, preliminary evaluation using nuSolve, product-based analysis with Calc/Solve, and final product preparation and delivery to the IVS data centers.

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2 Data Analysis at BKG

The initial data analysis is performed using the interactive geodetic VLBI software nuSolve [8]. The Mark 5 VLBI data analysis system Calc/Solve (release 2019.11.21) [3] processes the level 4 vgosDb output from nuSolve to generate IVS products. At the end of 2024, a new Calc/Solve software, release 2024.10.29 [4], was installed, and initial tests were successful.

Processing of Version 1 of the Wrapper File of the vgosDb Data Format: The BKG group continued the processing of the calibrated databases in the vgosDb format starting with the version 1 wrapper file. The vgosDb file set is filled, then, with the required reductions to generate the version 2 and 3 wrapper files

by means of nuSolve routines vgosDbCalc and vgosDbProcLogs. The corrections for the ambiguities and ionosphere are computed independently with nuSolve [8], where it is required, in the first step of the data analysis. In the second step, the minimum parameterization is applied in nuSolve to remove the outliers, and the final results are stored as the version 4 wrapper file.

Responsibility of the BKG AC for Delivering vgosDb Level 4 Data for OHIG and T2 Sessions: The BKG AC is responsible for the analysis of the OHIG and T2 sessions. BKG delivers the corresponding vgosDb level 4 data to the IVS data centers.

BKG's Analysis of 24-hour Sessions: At the beginning of 2023, the BKG EOP time series bkg2022a [2] was replaced by bkg2023a, incorporating an updated gravitational deformation model for VLBI telescopes, extended by seven stations. By the end of 2023, bkg2023b was introduced, now utilizing atmospheric pressure loading time series from GFZ Helmholtz-Zentrum für Geoforschung in Potsdam, Germany [5]. Additionally, the station coordinates of RAEGSMAR (Azores) and NYALE13S (Norway) were determined as global parameters, as their data now span over three years. Several new VGOS stations were successfully integrated: HARTVGS (South Africa), SESHAN13 (China), and URUMQI13 (China). With each new VLBI session preprocessing, a global solution was computed, covering over 6,640 24-hour S/X and VGOS sessions since 1984, forming the operational EOP time series bkg2023b. In this solution, station coordinates and velocities, source positions, and EOP were globally estimated. The datum definition was realized by applying no-net-rotation and no-net-translation conditions to 49 selected station positions and velocities with respect to ITRF2020 [7] and a no-net-rotation condition to 303 defining sources with respect to ICRF3 [6]. The station coordinates of the following telescopes were estimated as local parameters in each session: AIRA (Japan), CHICHI10 (Japan), CTVASTJ (Canada), DSS26 (USA), DSS34 (Australia), DSS36 (Australia), DSS56 (Spain), KASHIM11 (Japan), KASHIM34 (Japan), KOGANEI (Japan), OHIGGINS (Antarctica), PT_REYES (USA), SEST (Chile), SINTOTU3 (Japan), SVERT13V (Russia), TIDBIN64 (Australia), TIGOCONC (Chile), TSUKUB32 (Japan), UCHINOUR (Japan), VERAISGK (Japan), VERAMZSW (Japan), WARK30M (New Zealand), WIDE85_3 (USA), and YEBES40M (Spain).

BKG dUT1 *Intensive* **Time Series:** In 2023, the new dUT1 *Intensive* time series bkg2023a was introduced, similar to the EOP-S products, with the key difference from bkg2022a being the incorporation of a gravitational deformation model extended by seven stations. By the end of 2023, bkg2023a was replaced by bkg2023b, which now integrates atmospheric pressure loading time series from GFZ. The bkg2023b series is generated with station positions fixed to ITRF2020 and source positions fixed to ICRF3. The a priori EOP values are taken from the USNO finals time series [9]. The estimated parameters include UT1-TAI, station clocks, and zenith wet delay. Figure 1 shows the WRMS and bias of the estimated BKG dUT1 compared to Bulletin A.

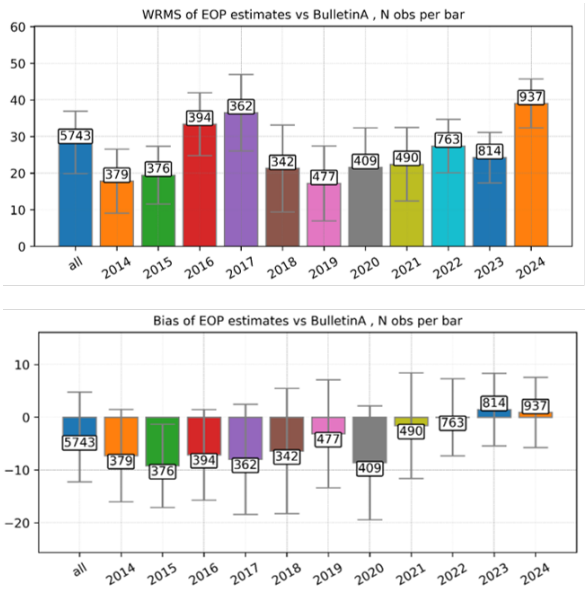

Fig. 1 WRMS and bias of dUT1 estimates from BKG's *Intensive* (INT) time series compared to Bulletin A, for the years 2014 – 2024. The number of sessions per year is indicated above each bar.

A total of 5,253 *Intensive* sessions was analyzed for the period from 2014.01.02 to 2024.12.30.

Quarterly Updated Solutions for Submission to IVS: In 2023, quarterly updated solutions were computed for the IVS TRF and CRF products, following the same computation strategy as the continuously generated EOP time series bkg2023b. Radio source positions were submitted to IVS in IERS format, while the TRF solution was provided in SINEX format ver-

sion 2.1, including station coordinates, velocities, the covariance matrix, constraint information, and the decomposed normal matrix and vector.

Tropospheric Parameters: Calc/Solve enables the generation of tropospheric path delay (TRP) files, providing parameter estimates based on Vienna Mapping Function (VMF1/VMF3) data. These files describe the troposphere on a scan-by-scan basis, including a priori slant delay, dry and wet mapping functions, and gradient mapping functions. VMF3 data were downloaded daily from the Vienna University of Technology server [10]. The BKG VLBI group has regularly submitted long time series of tropospheric parameters in SINEX format as IVS tropospheric products (wet and total zenith delays, horizontal gradients) for all VLBI sessions since 1984. In 2023, the new tropospheric time series bkg2023a and bkg2023b were introduced, aligning with other products. The extracted tropospheric parameters were transformed into tropospheric SINEX format for IVS submission.

Session-wise SINEX Files for 24-hour Sessions: The BKG VLBI group regularly submits session-wise SINEX files (bkg2023a, then bkg2023b) for 24-hour S/X and VGOS sessions, contributing to IVS combined products and baseline length time series. These daily files include session-wise estimates of station coordinates, radio source coordinates, and all EOP. The TRF datum is based on ITRF2020, while ICRF3 serves as the a priori CRF reference.

SINEX Files for *Intensive* Sessions: The creation of SINEX files for all *Intensive* sessions continued in 2023 and 2024. In early 2023, the bkg2022a solution was replaced by bkg2023a, followed by bkg2023b in mid-2024. The SINEX files include estimated parameters such as station coordinates, pole coordinates with rates, and UT1-TAI with its rate. This setup ensures that the normal equations in the SINEX files remain suitable for intra-technique and multi-technique combinations.

Contribution to ITRF2020-u2023: In early 2024, BKG submitted all 24-hour S/X and VGOS sessions (2021 – 2023) to the IVS Combination Center for the IVS contribution to ITRF2020-u2023. The parameterization remains consistent with the IVS product—daily SINEX files bkg2023b. The SINEX files contain the block with non-tidal atmospheric loading corrections applied in VLBI analysis, allowing these corrections to be removed at the combination level in order to meet ITRF requirements.

3 Developments

BKG utilizes various software packages for geodetic analysis, focusing not only on individual techniques but also on their combination to enhance reference frame and Earth rotation parameters. Our goal is to advance multi-technique combined analysis using a single software package, i.e., the Bernese GNSS Software (BSW). This will enable the integration of GNSS, VLBI, and SLR data not only at the SINEX level but also at the observation level, while also allowing BSW to be used for VLBI-only analysis. BSW, mainly developed by the Astronomical Institute of the University of Bern (AIUB), is continuously adapted to evolving requirements. Since 2021, BKG has been working closely with AIUB to extend BSW for VLBI data processing. Currently, BSW supports VLBI solutions based on normal equation input via SINEX files. However, additional implementation steps are required to process raw VLBI observations. The following milestones have been achieved so far:

- Implementation of VLBI observation model.
- Implementation of a flexible converter for VLBI observations from vgosDb (version 4) to BSW-internal format, allowing future extensions for processing also raw observations.
- Redesign of the generic observation file for multi-technique handling, incorporating one or more base objects (e.g., GNSS antennas, VLBI telescopes) and partner objects (e.g., GNSS satellites, quasars) within a single file.
- Design of an observation file handling object for the selection of observations.
- Design of the “space geodetic object class” to represent satellites, quasars, and ground objects, allowing them to function as base or partner objects in observation files based on the observation type.
- Design of a dynamic space geodetic object database, built during run-time to provide general information for processed base and partner objects.
- Introduction of new parameter “quasar coordinate”.
- Implementation of a clock model.

Further steps are required before VLBI sessions can be analyzed operationally using BSW, including automated detection and handling of clock breaks, as well as outlier screening. Additional VLBI-specific corrections must also be incorporated, such as cable calibration delays, thermal and gravitational antenna deforma-

Table 1 Summary of BKG VLBI Analysis Center Products

Product	Description
vgosDb Processing	vgosDb processing (versions 1 – 4) using `nuSolve` (`vgosDbCalc`, `vgosDbProcLogs`), including ambiguity and ionosphere corrections.
vgosDb Level 4 for OHIG and T2	BKG analyzes OHIG and T2 sessions, correlated at MPIfR/BKG, and delivers Level 4 vgosDb data to IVS.
24-hour Session Analysis	Transition from bkg2022a to bkg2023a/b. Updates include gravitational deformation, atmospheric pressure loading, and new VGOS stations.
BKG dUT1 *Intensive* Series	Creation of bkg2023a/b dUT1 *Intensive* series with updated models. Covers 5,253 sessions (2014 – 2024).
Quarterly IVS Updates	Quarterly TRF and CRF solutions, same strategy as bkg2023b. TRF submitted in SINEX 2.1 format.
Tropospheric Parameters	TRP files using VMF1/VMF3. Regular SINEX submissions to IVS. Introduction of bkg2023a/b.
Session-wise SINEX (24-hour)	SINEX files for 24-hour sessions (bkg2023a/b) include station coordinates, radio sources, and EOP.
SINEX for *Intensive* Sessions	SINEX files for *Intensive* sessions (bkg2023a/b), including station coordinates and EOP.
ITRF2020-u2023 Contribution	Submission of 24-hour S/X and VGOS sessions (2021 – 2023) for IVS ITRF2020-u2023 contribution.

tions, and the galactic aberration effect. More details can be found in [11] and [12]. [12] also reports systematics in the O-C residuals caused by an implementation bug, which has now been fixed.

4 Research Topics at BKG

BKG's ongoing research focuses on improving the temporal regularity and accuracy of EOP series, particularly the UT1-UTC component, through an intra-technique combination of all VLBI session types. Currently, the IVS analyzes EOP separately using two VLBI session types: 24-hour and one-hour *Intensive* sessions, each with distinct strengths and limitations. The 24-hour sessions (EOP-S series) provide high accuracy from global network observations but suffer from irregular resolution and delayed availability. In contrast, *Intensive* sessions (EOP-I series) offer daily data but with lower dUT1 estimation accuracy due to short observation duration, irregular resolution, and a limited network that prevents estimating other EOP. To address these limitations, BKG has developed an intra-technique combination method that integrates data from both session types into a unified EOP analysis, enhancing consistency and precision.

As input data, we use SINEX files provided by the BKG AC. The combination processing is performed using the Combination and Solution package of the DGFI Orbit and Geodetic Parameter Estimation Software (DOGS-CS), developed and maintained at DGFI-TUM (Deutsches Geodätisches Forschungsinstitut, Technische Universität München). Initial research by [13] demonstrated significant improvements by combining *Intensive* and Rapid sessions using a normal equation (NEQ) level combination approach (as shown in Figure 2). This

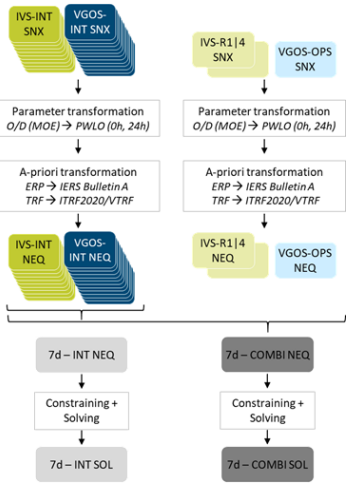

Fig. 2 Schematic representation of the seven-day VLBI intra-technique combination strategy for UT1-UTC estimation.

method applies a seven-day processing window with continuous piecewise linear (PWL) parameterization of the EOP. By integrating VLBI data from the last seven days and estimating EOP as continuous PWL polynomials, this approach stabilizes parameter estimates and reduces random deviations by leveraging prior-day information. The approach successfully generated a continuous, daily, and regularly-spaced UT1-UTC series, where we can reach significantly reduced weighted root mean square (WRMS) errors: The WRMS values of the UT1-UTC residuals were analyzed against the IERS Bulletin A series. A single-session *Intensive* solution yielded a WRMS of 23.2 μs, which decreased to 18.8 μs with a seven-day *Intensive* session combination (7d-INT). Further improvement was achieved by incorporating Rapid sessions into the seven-day combination (7d-COMBI), reducing the WRMS to 13.8 μs. These values correspond to the middle day of the seven-day arc, representing a 41%

Table 2 Staff members of BKG's VLBI AC during 2023/2024.

Name	Function	Changes
Gerald Engelhardt	Lead; Analysis strategy; operational VLBI analysis	
Anastasiia Walenta	Software Management; VLBI analysis; scientific studies	until June 2024
Sadegh Modiri	Operational VLBI analysis; scientific studies	since August 2024
Markus Goltz	Operational VLBI analysis; Software Management	since March 2024
Christian Schade	Operational VLBI analysis; Software Management	since August 2024
Dieter Ullrich	Operational VLBI analysis	until June 2023
Claudia Flohrer	VLBI developments Bernese Software; scientific advice	
Lisa Klemm	VLBI-internally combined EOP series; scientific studies	
Daniela Thaller	Scientific and strategic advice	

reduction compared to the single-session *Intensive* solution and a 27% improvement over the *Intensive*-only combination, demonstrating the advantages of multi-session and combined processing for enhancing UT1-UTC accuracy.

This initial study focused exclusively on combining VLBI legacy sessions. Recent developments at BKG have enhanced the intra-technique combination approach by integrating additional session types, particularly from VGOS. Over the last five years, the increased frequency and consistency of VGOS sessions have improved the stability and reliability of EOP estimation. While WRMS values compared to IERS Bulletin A have not decreased further, the inclusion of VGOS *Intensive* sessions has significantly densified the UT1-UTC time series, filling gaps caused by missing data. This has improved the overall reliability and continuity of UT1-UTC estimates, addressing previous challenges with data availability and network configuration.

However, integrating VGOS 24-hour sessions (VGOS-OPS) has introduced new challenges, raising WRMS values to 17.6 μs for the middle day of the seven-day arc, compared to solutions without VGOS-OPS data. This deterioration is suspected to stem from inaccuracies or insufficient quality in the coordinates of newly established VGOS stations, highlighting the need for regular updates to the reference frame to maintain high-quality geodetic products.

Despite this, the enhanced methodology consistently improves UT1-UTC accuracy, temporal continuity, and robustness, making it more comparable with other space geodetic techniques and providing more reliable input for EOP predictive algorithms. Future work at BKG will focus on refining the combination process and datum definition to optimize VGOS data integration and continuously improve the quality and usability of VLBI-derived geodetic products.

5 Personnel

Table 2 lists the members of the BKG VLBI AC for 2023 and 2024, including changes during this period.

6 Future Plans

In 2025 and 2026, the work of BKG's VLBI analysis group will focus on the following aspects:

- Generation of BKG's contribution to the second yearly update of ITRF2020, i.e., ITRF2020-update2024.
- Develop and implement an automated VLBI data analysis, especially for INT sessions, in order to reduce the latency.
- Improve and extend the quality control of the VLBI analysis process and resulting products.
- Provide VLBI-only EOP series by combining 24-hour and INT sessions on an operational daily basis.
- Develop the VLBI capabilities of the Bernese GNSS Software further in order to be ready for a (basic) VLBI analysis.
- Re-launch of the VLBI website at BKG.
- Establish EOP predictions based on BKG's VLBI-based EOP products.

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