# BKG/DGFI-TUM Combination Center

Sabine Bachmann[1], Hendrik Hellmers[1], Sadegh Modiri[1], Sandra Schneider-Leck[1], Mathis Bloßfeld[2], Daniela Thaller[1]

**Abstract** This report summarizes the activities of the BKG/DGFI-TUM Combination Center in 2021 and 2022 and outlines the planned activities for 2023 and 2024. The main focus in 2021 and 2022 was submitting the IVS contribution to the ITRF2020. Furthermore, we included additional Analysis Centers in the combined solution. In 2023 and 2024, we intend to improve the combination strategy for small station networks, to expand the consistent realization for EOP, and to evaluate the impact of the different ITRS realizations (DTRF2020, ITRF2020, and JTRF2020) on the combined EOP.

## 1 General Information

The BKG/DGFI-TUM Combination Center was established in October 2008 as a joint effort of the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, or BKG) and the German Geodetic Research Institute (Deutsches Geodätisches Forschungsinstitut, or DGFI). The participating institutions, as well as the tasks and the structure of the IVS Combination Center, are described in [12]. The tasks comprise quality control and a timely combination of the session-based intermediate results of the IVS Analysis Centers (ACs) into a final combination product (e.g., Earth orientation parameters, or EOP). In coordination with the IVS Analysis Coordinator, the combination results are released as official IVS products. The Combination Center is also expected to contribute to generating the official IVS input for any ITRF activities.

The BKG/DGFI-TUM Combination Center performs a combination of session-based results of the IVS ACs on an operational basis. The strategy for the combination is based on the combination of normal equations and was adopted from the combination process as developed and performed by the IVS Analysis Coordinator (cf. [10], [11]).

At BKG, the following tasks are performed:

- Quality control of the AC results: checking the format of the results and their suitability for combination, identification, and reduction of outliers, comparison of the Analysis Centers' results with each other, and comparison of the results with external time series provided by the IERS, IGS, and ILRS.
- Feedback to the Analysis Centers: quality control results are available on the BKG IVS Combination Center web pages [8].
- Generation of high-quality combination products and timely archiving and distribution: combination products are created by using the combination part DOGS_CS of DGFI-TUM's software package DOGS (DGFI orbit and geodetic parameter estimation software) [3].
- Submission of official IVS combination products to the IERS: the products are submitted to the responsible IERS components to be used for IERS product generation (e.g., for EOP rapid products and the EOP series IERS C04).
- Generation of the official IVS input to the ITRF: the combined session products (from 1979 to present) are submitted for ITRF computation in the form of normal equations in SINEX format [4]. This work

1. Federal Agency for Cartography and Geodesy (BKG)
2. Technische Universität München, Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)

is also supported by the staff of the IERS Central Bureau hosted by BKG.
- Final results are archived in the BKG Data Center and mirrored to the IVS Data Centers at Observatoire de Paris (OPAR) and the Goddard Space Flight Center (GSFC). This work is assisted by the staff of the BKG Data Center.

DGFI-TUM is in charge of the following Combination Center functions:

- DGFI is developing state-of-the-art combination procedures. This work, as well as the following item, is related to the ITRS Combination Center at DGFI.
- The software DOGS_CS is updated by implementing and documenting the developed state-of-the-art combination procedures.
- The DGFI DOGS software package is continuously updated to be in accordance with the IERS Conventions.

## 2 Activities during the Past Two Years

At BKG, the following activities were performed in 2021 and 2022:

- Integration of the new DOGS_CS software into the IVS combination process.
- Generation of a combined solution for IVS 24-hour rapid sessions twice a week.
- Generation of a combined long-term solution of IVS 24-hour sessions every three months.
- Ensuring that the combination process is in agreement with the IERS2010 Conventions.
- Generation of the IVS combined contribution to the ITRF2020 for the IERS ITRS Combination Centers.
- Validation of the ITRF2020 solution and investigation of the scale behavior as a contribution to the IVS Working Group.
- Pilot project on piecewise linear EOPs: generation and validation of the combined EOP solution.
- Inclusion of new ACs: Vienna University of Technology (VIE) into the routine rapid combination.
- Testing of potential new ACs: University of Alicante, Spain (UAV).
- Refinements of the combination procedure and implementation of source position combination.

For the operational rapid combination, the contribution of one additional AC was added; AC VIE using VieVS was introduced in the combination routine. This increases the number of regularly contributing ACs to 12.

At DGFI-TUM, the following activities were performed in 2021 and 2022:

- Construction and integration of restitution equations.
- Update of the similarity transformation program.

### 2.1 IVS Contribution to ITRF2020

One of the main tasks was the submission of the IVS contribution to the ITRF2020 and its evaluation. The IVS contribution to the ITRF2020 was finalized and submitted to the IERS ITRS Combination Centers in the beginning of June 2021. Altogether eleven ACs contributed with their reprocessed series, and the variety of software packages used by the ACs could be greatly increased to seven. The reprocessed series contains approximately 6,500 sessions. For the first time, an ITRF also contains VGOS sessions so that station coordinates for the new VGOS sites could be estimated along with the legacy network. Overall, 171 different stations observed between 1979.0 and 2021.0 are included in the contribution. Thereby the number of stations could be increased by five in comparison to the previous ITRF2014.

For the evaluation of the combined contribution, various investigations were made in order to ensure high quality of the submitted files. Figure 1 shows the WRMS values for both the stations and the Earth's rotation (Polar Motion, dUT1) for the combined and the individual AC solutions. As expected, an improvement of the statistics for the combined solution is evident. More details on the combined IVS contribution can be found in [4] and [6].

The IVS Combination Center also contributed to the IVS Working Group for investigating the suspicious behavior of the scale time series seen by the ITRF2020 [5]. Figure 2 shows the scale of single combined sessions with respect to DTRF2020 preliminary (orange), ITRF2014 (magenta), and ITRF2020 (black). An improvement for ITRF2020 compared to ITRF2014 is clearly seen. But the behavior for the most recent years still needs to be understood.

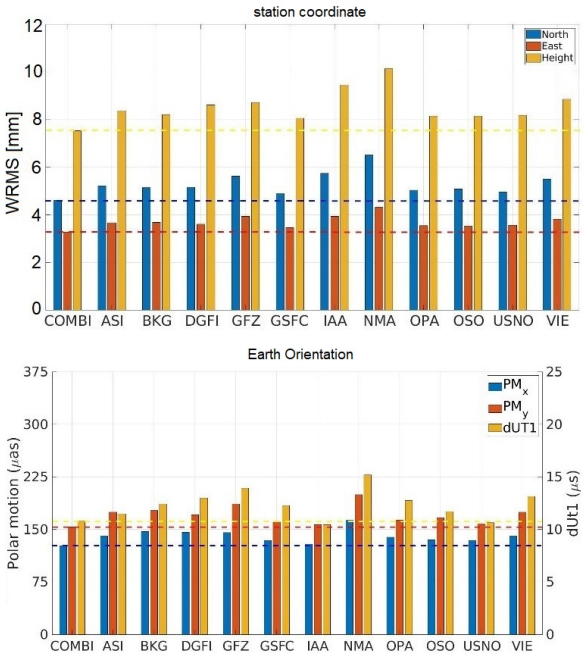


**Fig. 1** Station coordinate WRMS of all stations (upper figure). WRMS for Polar Motion and dUT1 (lower figure).

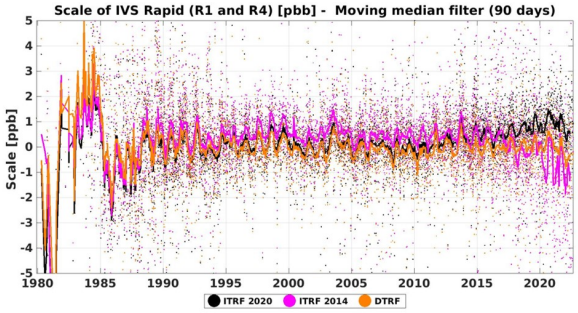


**Fig. 2** Scale between single combined sessions and DTRF2020 preliminary (orange), ITRF2014 (magenta), and ITRF2020 (black).

## 2.2 Project on Six-hourly EOP Piecewise Linear Offset Parameterization

While the estimation of Earth Orientation Parameters (EOP) in conventional VLBI sessions is done at the midpoint of the 24-hour observation interval, the parameterization of EOP in this project is done with continuous piecewise linear functions w.r.t. six-hour intervals [9]. Because most IVS sessions observe between 18h00 UT on the start day and 18h00 UT on the following day, the EOP estimates refer to the mean observation epoch of 6h00 UT on the following day. As a result, the corresponding EOP rate, which is interpolated on the basis of the second and the third day boundary, represents only 3/4 of the entire observation interval. Figure 3 shows the representation of an EOP rate for conventional 24-hour VLBI sessions. Because this

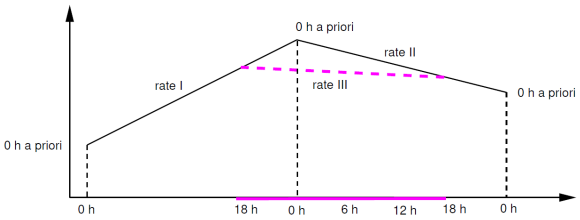


**Fig. 3** Representation of EOP rate for a generic observing session from 18h00 UT to 18h00 UT.

EOP representation differs from the representation in other space geodetic observation techniques (the standard representation is from 0h00 UT to 24h00 UT), the parameterization of the EOP in this project is done continuously piecewise linear in a six-hour interval. The corresponding EOP offsets refer to the epochs 18h00 UT – 0h00 UT – 6h00 UT – 12h00 UT – 18h00 UT (Figure 4), so that the resulting estimates can be clearly compared with the estimates of other space geodetic observation techniques.

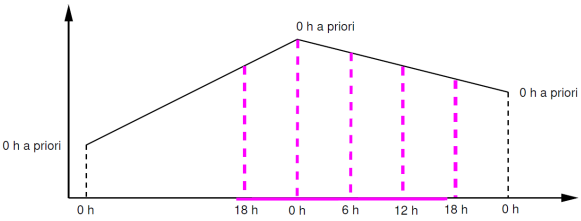


**Fig. 4** Six-hourly intervals for a generic observing session from 18h00 UT to 18h00 UT.

In order to validate the estimated EOP, we calculated a time series based on 52 IVS-R1 sessions in 2020 with six-hour piecewise linear offsets. In this case, four different IVS Analysis Centers provided pre-analyzed normal equations included in the SINEX file format. Because of the cross-day observation interval, we estimated the EOP offsets of all individual contributions,

**Table 1** Staff members of the BKG/DGFI-TUM Combination Center.

| Name | Affiliation | Function | E-Mail |
|---|---|---|---|
| Sabine Bachmann | BKG | Combination procedure development | sabine.bachmann@bkg.bund.de |
| Hendrik Hellmers | BKG | ITRF2020; Combination procedure | hendrik.hellmers@bkg.bund.de |
| Sadegh Modiri | BKG | ITRF2020; Operational combination | sadegh.modiri@bkg.bund.de |
| Sandra Schneider-Leck | BKG | Operational combination | sandra.schneider-leck@bkg.bund.de |
| Sonja Geist | BKG | IVS CC Web pages | sonja.geist @bkg.bund.de |
| Daniela Thaller | BKG | Scientific and strategic advice | daniela.thaller@bkg.bund.de |
| Mathis Bloßfeld | DGFI-TUM | DOGS_CS; Combination strategies | mathis.blossfeld@tum.de |

as well as a combined solution at times 12h00 UT – 18h00 UT – 0h00 UT – 6h00 UT – 12h00 UT – 18h00 UT. The calculation of the combination was carried out by the IVS Combination Center at BKG by applying equivalent procedures as for ITRF2020 [4]. Because the nutation and the pole coordinates cannot be determined independently of each other with this parameter setup, we used conditions in the form of known sine periods for the celestial pole offsets.

For investigating the accuracy of Polar Motion and dUT1, the differences were determined with respect to the IERS 14 C04 time series, which is used as a reference. The EOP epochs were interpolated within the corresponding days, accordingly.

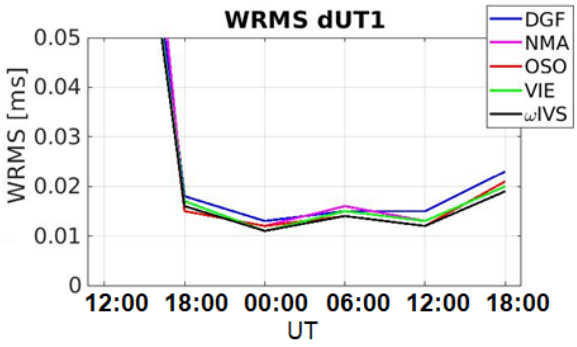


**Fig. 5** WRMS of six-hourly dUT1 estimates compared to IERS 14 C04.

Figure 5 shows the resulting Weighted Root Mean Square values of dUT1 at the corresponding epochs of the day. Because the first day is outside the observation interval, the resulting deviation from the reference series is not representative. The other estimates are in the range of 15 $\mu$s. In this case, the combination solution shows slightly lower WRMS values. Although the deviations per time of day are slightly higher than the deviations with the conventional offset/drift representation (a WRMS value of up to 10 $\mu$as can be expected for the dUT1), the resolution of the ERP estimate can be increased by the six-hour parameterization. Consequently, consistent comparisons with other space geodetic observation techniques are possible. Thus, the use of continuous piecewise linear estimation is the next step in VLBI analysis. Moreover, it has been demonstrated that it is possible to obtain a correct representation of ERP rates for observation intervals extending beyond midnight.

## 3 Staff

The list of the staff members of the BKG/DGFI-TUM Combination Center in 2021 and 2022 is given in Table 1.

## 4 Current Status

By the end of 2022, 12 IVS ACs (ASI, BKG, DGFI-TUM, GFZ, GSFC, IAA, IGE, NMA, OPA, OSO, USNO, and VIE) contributed regularly to the IVS combined rapid and quarterly products (see [8]). The AC UAV (University of Alicante, Spain) is currently under review and will probably become an IVS Operational AC in the near future. The rapid solutions only contain R1 and R4 sessions, and new data points are added twice a week as soon as the SINEX files of at least four IVS ACs are available. Long-term series are generated quarterly and include all 24-hour sessions since 1984. The quarterly series include long-term EOP, station positions, and velocities. Furthermore, a VLBI TRF is generated and submitted to the IVS Data Centers.

The IVS combined EOP series have been submitted in the new EOP format version 3 since the beginning of 2023.

Several tests of new software versions are in progress to prepare for the transition from the ITRF2014 to the ITRF2020 reference frame. The transition is planned for March 2023.

The results of the combination process are archived by the BKG Data Center. Unfortunately, the IVS Combination Center website [8] has been offline for quite some months now. We are working on its re-establishment, so that the combined rapid EOP series, as well as the results of the quality control of the AC results, will soon be available directly at the website again. Meanwhile, some of this information is accessible also via the IVS Analysis Coordinator website.

## 5 Future Plans

In 2023 and 2024, the work of the BKG/DGFI-TUM Combination Center will focus on the following aspects:

- Implementation of the new master file format.
- Transition to ITRF2020 in the first months of 2023.
- Investigating the impact of different ITRS realizations (DTRF2020, ITRF2020, and JTRF2020) on the combined EOP.
- Including new ACs into the routine rapid and quarterly combination.
- Improving the combination strategy.
- Re-launch of the IVS Combination Center website.
- Establish EOP predictions based on IVS combined EOP products.

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