Analysis of Legacy and VGOS Intensives at IVS AC DGFI-TUM

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Abstract Since 2008, DGFI-TUM is an operational Analysis Center (AC) of the International VLBI Service for Geodesy and Astrometry (IVS). We submit datum-free normal equations for the rapid turnaround sessions (R1/R4) to the IVS Combination Center on a weekly basis, and we provide the same type of data for all other 24-hour sessions at less regular time intervals. Recently, we set up an automated process to analyze the VLBI Intensive sessions, which are performed to determine the dUT1 parameter on a daily basis. The Intensives have a duration of only one hour and mostly consist of a single East-West baseline. Thus, their latency is much lower compared to the R1/R4 sessions. With the establishment of the next-generation VLBI Global Observing System (VGOS), two Intensive sessions with different observation modes are available per day. At DGFI-TUM, we analyze the main Intensive series of both observation modes, i.e., IVS-INT-1 and IVS-INT-2 of the legacy system, and the respective VGOS-INT-A and VGOS-INT-B of the VGOS. In this paper, we take a look at the distinct Intensive series, describe our analysis setup, and compare the corresponding dUT1 results for the various baselines and observation modes. Furthermore, we check our Intensive dUT1 values and their formal errors against those obtained from the 24-hour sessions, against those of other ACs, and against combined inter-technique dUT1 series. In the end, we desire DGFI-TUM's Intensive session normal equations to become part of various intra- and inter-technique dUT1 combinations.

Keywords Intensives, VGOS

1. Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM)

1 Introduction

Various Very Long Baseline Interferometry (VLBI) Intensive series have existed for about 40 years. Robertson et al. [7] have shown that these are capable of determining the time-variable speed of Earth rotation, often expressed as dUT1 = UT1–UTC, by observing a single long East-West baseline for one hour. Today, there are daily Intensive sessions for the rapid determination of dUT1, and since about 2020 there even are (at least) two such sessions per day: one in legacy VLBI mode, and one performed with the next-generation VLBI Global Observing System (VGOS). DGFI-TUM is an Analysis Center (AC) of the International VLBI Service for Geodesy and Astrometry (IVS), and we recently set up an automated process to analyze these daily Intensive series with the Radio Interferometry component of our DGFI Orbit and Geodetic parameter estimation Software (DOGS-RI). Here we relate our initial results to those of other IVS ACs. Furthermore, we compare all dUT1 results with the values obtained from external Earth orientation parameter (EOP) series, which have been created by the combination of several geodetic space techniques.

2 Input Data

In Table 1, we summarize the four Intensive series that we have analyzed for this work. These are the legacy series IVS-INT-1 and IVS-INT-2, observing during the week and at the weekend, respectively, and the corresponding VGOS series VGOS-INT-A and VGOS-INT-B. Except for the weekend sessions after September 2023, the legacy and VGOS series were

Table 1 Details of the four Intensive series used in this study. The percentages refer to the period 2020.0–2024.0.

series	mode	IVS code	observation time [UTC]	most frequent station networks
IVS-INT-1	legacy	i (XU)	Mon–Fri 18:30 (before 10/23) 17:30 (since 10/23)	KOKEE, WETTZELL (≈ 81%) KOKEE, WETTZELL, SVETLOE (≈ 5%) MK-VLBA, WETTZELL (≈ 4%)
IVS-INT-2	legacy	q (XK)	Sat–Sun 07:30	MK-VLBA, WETTZELL (≈ 57%) MK-VLBA, WETTZELL, ISHIOKA (≈ 19%) KOKEE, WETTZELL and WETTZELL, ISHIOKA (≈ 11%)
VGOS-INT-A	VGOS	v (VI)	Mon–Fri 18:30 (before 10/23) 17:30 (since 10/23)	KOKEE12M, WETTZ13S (≈ 83%) KOKEE12M, ONSA13NE (≈ 11%)
VGOS-INT-B	VGOS	b (VB)	Sat–Sun 07:30 (03/22–09/23) 05:30 (since 10/23)	ISHIOKA, ONSA13NE, ONSA13SW (≈ 65%) ISHIOKA, ONSA13NE (≈ 22%) ISHIOKA, ONSA13SW (≈ 13%)

run simultaneously. We included all available sessions between 2020.0 and 2024.0 with V004 vgosDB data.

The VGOS-INT-B series involves three stations: the twin-telescopes at Onsala, Sweden, and ISHIOKA in Japan. The other series mainly involve antennas at Kokee Park, Hawaii, and Wettzell, Germany, but with different pairs: KOKEE–WETTZELL in IVS-INT-1, MK-VLBA–WETTZELL in IVS-INT-2, and KOKEE12M–WETTZ13S in VGOS-INT-A. Other antennas also participate occasionally. As the VGOS broadband antennas are usually more sensitive and slew faster, there are about 2–3 times more observations per baseline in the VGOS Intensives. But in the legacy IVS-INT-2 series, the number of observations is often comparable to or even greater than that in VGOS-INT-A. The main reasons are (i) the contributions of the antenna MK-VLBA, which has a larger sensitivity than KOKEE and hence needs to spend less time at each radio source, and (ii) an improved scheduling for IVS-INT-2 since mid-2020 (Schartner et al., [8]). The VGOS-INT-B Intensives create the most observations, because three stations are involved, but the series has only observed regularly since 2022.

3 Analysis Results

In the analysis of the distinct Intensive series with DOGS-RI, we estimate six parameters with the Gauss-Markov model:

- a constant dUT1 value,
- the quadratic clock offset (three parameters per station) w.r.t. the reference station clock, and
- a single zenith wet delay per station.

Station positions, radio source coordinates, and the remaining EOPs are fixed to the ITRF2020 (incl. post-seismic deformation, excl. seasonal signals), the ICRF3, and the IERS 20 C04 series, respectively. The other geophysical models comply with the IERS 2010 Conventions [6], and we apply site displacements due to non-tidal atmospheric loading (NTAL) as provided by the Earth System Modelling group of the Deutsches GeoForschungsZentrum [3]. The parameterization does not differ between legacy VLBI and VGOS Intensives, and when we compared dUT1 values at different epochs, we used a cubic spline interpolation of the regularized (with 62 zonal tides) dUT1S values.

Before we turn to the results, we need to note that we present a reprocessed data set here. That means that we used final EOPs as a prioris and we did not need to care about the latency of daily products such as tropospheric mapping functions and NTAL site displacements. For (near) real-time analysis, rapid/predicted EOPs and other approximations must be applied.

3.1 Precision and Accuracy

In Table 2, we see that the precision of the estimated corrections to the a priori dUT1 from the IERS 20 C04 series, i.e., the formal error of the estimates, is inversely proportional to the average number of observations in the corresponding Intensive series. In particular, a legacy Intensive (IVS-INT-2) can provide formal errors similar to a VGOS Intensive (VGOS-INT-A) if the number of observations is also similar. On the other hand, the accuracy of the VGOS dUT1, represented by the weighted root mean square (WRMS) values of the correction time series w.r.t. IERS 20 C04,

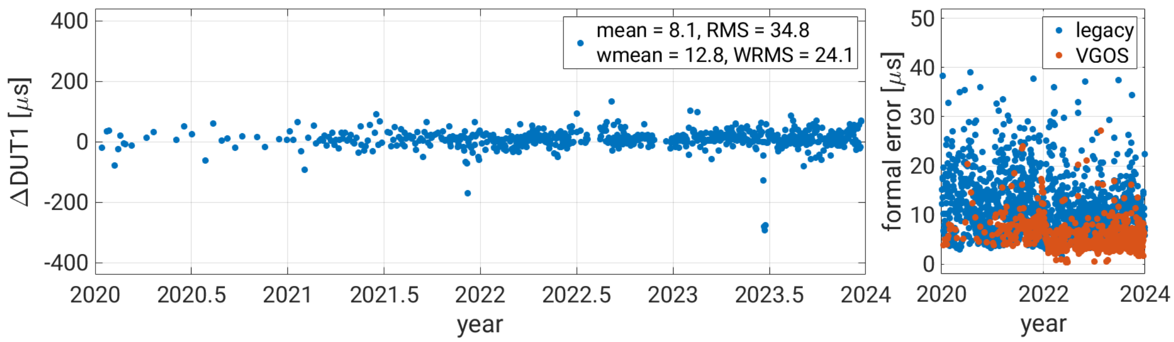

Fig. 1 Differences between dUT1 values estimated from the legacy and the VGOS Intensive series (left) as well as their respective formal errors (right).

is not significantly different from that of the legacy Intensives. This might confirm the discrepancy between theoretical and actual precision of the dUT1 estimates (compare, e.g., Dieck [2]), even for the VGOS measurements with their smaller formal errors, or indicate remaining inaccuracies in the C04 series.

Table 2 Statistics of the formal errors and of the time series of the corrections to a priori dUT1 in the distinct Intensive series. All values are given in [µs].

series	mean error	median error	weighted mean of corrections	WRMS of corrections
IVS-INT-1	13.58	12.00	2.68	25.31
IVS-INT-2	7.47	6.33	9.88	29.14
VGOS-INT-A	6.11	5.33	−4.89	26.35
VGOS-INT-B	3.72	3.33	1.84	28.95

3.2 Legacy vs. VGOS

Figure 1 shows the difference time series of the dUT1 estimates from the legacy and the VGOS Intensives. We observe a weighted mean offset of about 13 µs, which can approximately be deduced also from the differences in the weighted means of corrections in Table 2. This offset is larger than the mean or median formal errors of the VGOS and the INT-2 series. However, it is smaller than all the WRMS values of the corrections to a priori IERS 20 C04. Hence, the significance of this offset needs to be further investigated. The right panel of Figure 1 confirms the general superiority of the formal errors of VGOS as indicated by Table 2.

3.3 Comparison with Other ACs and Combined EOP Series

We downloaded Intensive dUT1 results by four other IVS ACs from the Crustal Dynamics Data Information System (CDDIS, *https://urs.earthdata.nasa.gov/*). In particular, these are stored in the files *bkg2023a.eopi* (Bundesamt für Kartographie und Geodäsie, BKG), *gsf2023a.eopi* (Goddard Space Flight Center, GSFC), *usn2023c.eopi* (US Naval Observatory, USNO), and *vie2023a.eopi* (Technische Universität Wien, TUW). Our solution code for this comparison is *dgf2023a*, because we use the same models as in our current solutions for the 24-hour sessions.

As an example, we show the difference time series w.r.t. GSFC for the legacy Intensives in Figure 2. We observe a systematic offset of −12.6 µs and an annual signal for the dUT1 differences. A similar offset was obtained w.r.t. USNO, and a similar annual signal appeared w.r.t. BKG. Only the difference time series w.r.t. TUW was unremarkable, while all ACs estimate formal errors of comparable magnitude.

The annual signal in the differences becomes even more striking for the dUT1 values estimated from the VGOS sessions (see Figure 3). The reason is the application of a priori corrections to the precession-nutation model, i.e., the celestial pole offsets (CPOs) ΔX and ΔY, as already mentioned by Malkin [4] or Dieck [2], for example. BKG and GSFC do not apply the CPOs, while the other ACs treated in this work do. For confirmation, we computed a second solution in which we removed the CPOs, too, and when looking at the difference time series w.r.t. *dgf2023a*, basically the same annual signal is revealed (see Figure 3). According to

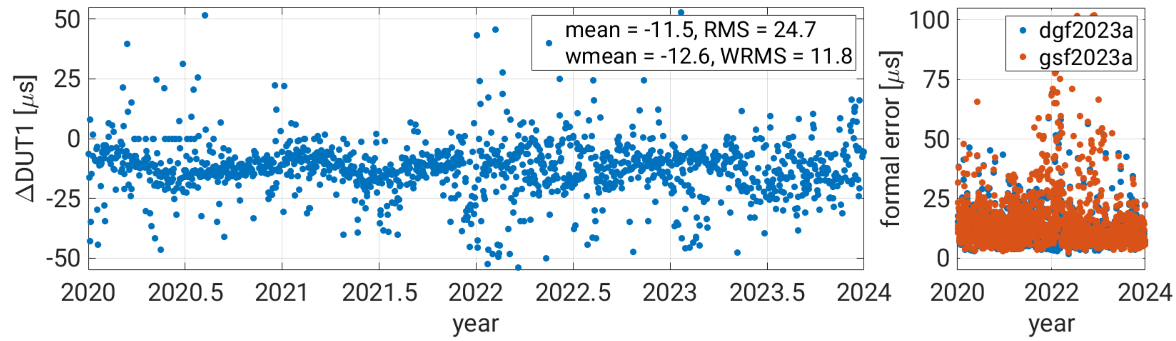

Fig. 2 Differences between our dUT1 values and those of GSFC (left), estimated from the legacy Intensive series, as well as their respective formal errors (right).

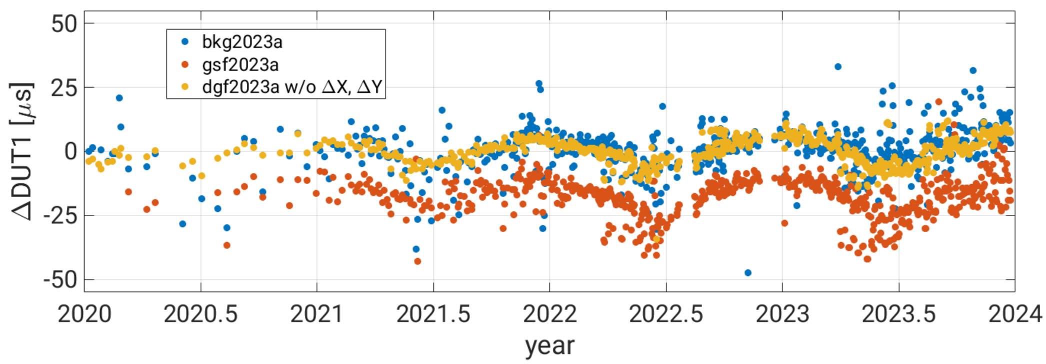

Fig. 3 Differences between our original dUT1 values and those of BKG (blue), GSFC (red), and a second solution in which we did not apply the corrections ΔX, ΔY to the precession-nutation model (yellow). dUT1 has been estimated from the VGOS Intensive series in each case.

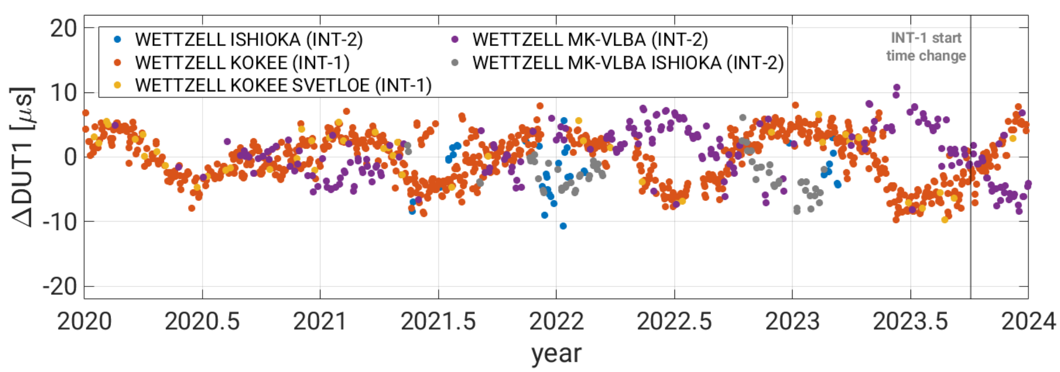

Fig. 4 Differences between our original dUT1 values and those of a second solution in which we did not apply the CPOs ΔX, ΔY. Here, dUT1 has been estimated from the legacy Intensive series, and we distinguish the differences per baseline.

Nothnagel and Schnell [5], the signal is further related to the difference between sidereal and solar time, and so its phase depends on the start times of the Intensive series, as shown in Figure 4.

The offset in the dUT1 difference time series is generated by deviating a priori station positions (e.g., Dieck and Johnson [1]). While BKG and TUW apply the ITRF2020 like us, GSFC and USNO use their own global solutions. Nothnagel and Schnell [5] provide derivatives of dUT1 w.r.t. the a priori positions, and their formula predicts changes in dUT1 quite similar to those shown in Figure 5. It presents the (reversed)

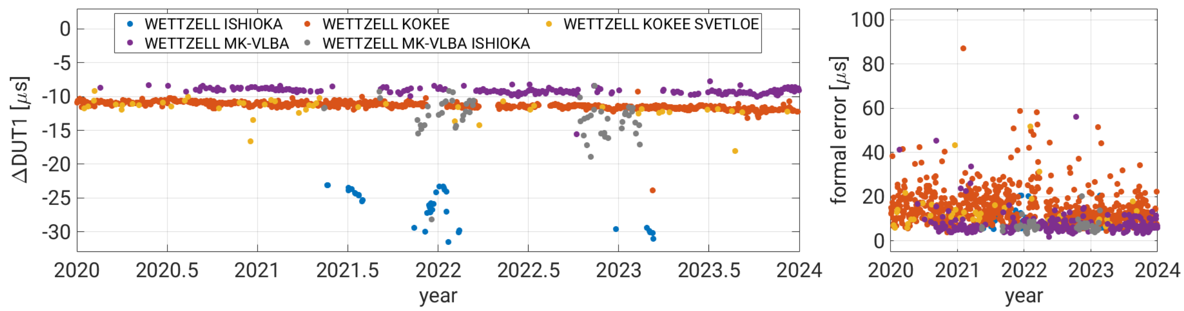

Fig. 5 Differences between the legacy dUT1 values of a third solution, in which we replaced the a priori station positions of the ITRF2020 with those of USNO's global solution, and our original legacy dUT1 values (left); original formal errors (right).

Table 3 Statistics of the dUT1 differences w.r.t. the combined IERS 20 C04 series. All values are given in [μs].

	legacy		VGOS	
solution	wmean	WRMS	wmean	WRMS
gsf2023a	22.0	32.6	17.2	30.4
usn2023c	21.7	31.4	n/a	n/a
bkg2023a	9.8	34.8	3.1	31.7
vie2023a	13.2	33.3	7.6	31.7
dgf2023a	8.7	30.4	2.8	28.3

differences in dUT1 estimated from legacy Intensives when replacing the ITRF2020 with the global solution of USNO for our a priori station positions. Of course, each baseline creates its own mean offset.

Finally, we computed the weighted mean (wmean) and WRMS values of the differences between the ACs' Intensive dUT1 and the values from external combined EOP series. As an example, the results for IERS 20 C04 are listed in Table 3 and separated by legacy and VGOS Intensives (there were no VGOS values in *usn2023c.eopi*). While the WRMS matches quite well for all ACs and between the VLBI generations, the offsets due to their own a priori station positions are again revealed for GSFC and USNO.

4 Conclusions

The dUT1 values and formal errors of our new (reprocessed) Intensives solution are in line with the results of other ACs, for both the daily legacy and the daily VGOS series. Systematic offsets can be traced back to differences in a priori station positions, while deviations with annual periods mainly stem from the omission of (a priori) CPOs. Both effects depend on the sessions' baselines and/or start times. There might be a systematic offset between dUT1 obtained from legacy and VGOS Intensives that needs further investigation.

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