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Improving dUT1 from VLBI intensive sessions with GRAD gradients and ray-traced delays

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Abstract

Exact knowledge of the angle of Earth rotation UT1 with respect to coordinated time UTC, dUT1, is essential for all space geodetic techniques. The only technique which is capable of determining dUT1 is Very Long Baseline Interferometry (VLBI). So-called Intensive VLBI sessions are performed on a daily basis in order to provide dUT1. Due to the reduced geometry of Intensive sessions, there is however no possibility to estimate tropospheric gradients from the observations, which limits the accuracy of the resulting dUT1 significantly. This paper deals with introducing the information on azimuthal asymmetry from external sources, thus attempting to improve the dUT1 estimates. We use the discrete horizontal gradients GRAD and the empirical horizontal gradients GPT3 as well as ray-traced delays from the VieVS ray-tracer for this purpose, which can all be downloaded from the VMF server of TU Wien (http://vmf.geo.tuwien.ac.at). The results show that this strategy indeed improves the dUT1 estimates when compared to reference values from multi-station VLBI stations, namely by up to 15%. When converted to length-of-day (LOD), the estimates can be compared to LODs from global analyses of Global Navigation Satellite Systems (GNSS). Here, the improvement amounts to up to 7% compared to neglecting a priori information on azimuthal asymmetry.

Keywords: dUT1; VLBI; Earth rotation; Horizontal gradients; Ray-tracing; Numerical weather models

1. Introduction

Earth Orientation Parameters (EOPs) describe the attitude of the Earth's rotational axis in space. In other words, they represent the five elements which are necessary for transformations between a terrestrial reference frame (TRF) and a celestial reference frame (CRF). The two polar motion components x_P and y_P quantify the motion of the Earth's rotational axis with respect to its crust. Precession and nutation models describe the orientation of the rotational axis with respect to space. The fifth parameter, dUT1, corresponds to the difference between Universal Time UT1 (which is based on Earth rotation) and Coordinated Universal Time UTC (which is realized through atomic clocks).

Among the EOPs, dUT1 is the most variable quantity containing significant unpredictable variations (Nothnagel and Schnell, 2008), which implies variations in the Earth's angular velocity and consequently in length of day (LOD). The causes for the variations are mainly solid Earth tides and movements in the atmosphere, while effects of the liquid outer core, ocean tides and ocean currents contribute to a lesser extent (Böhm, 2010). Unlike the other EOPs, dUT1 can only be measured with Very Long Baseline Interferometry (VLBI), as satellite techniques are not capable of distinguishing between changes in the orbital parameters of the satellites and in the rotational phase of the Earth. For this reason, Global Navigation Satellite Systems

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(GNSS) are dependent on VLBI as they need dUT1 to maintain its operability.

dUT1 can be estimated within VLBI analysis of a station network consisting of at least two stations. In order to guarantee high sensitivity to Earth rotation, VLBI baselines with a long east-west extension are required. In theory, it would be most appropriate to have a globally distributed multi-station network, performing as many observations as possible, from which dUT1 and further quantities such as the other four EOPs, zenith wet delay, tropospheric gradients and clock parameters can be estimated. However, such multi-station networks measuring on a daily basis are not feasible. Therefore, only single-baseline (occasionally double-baseline) sessions are carried out. These sessions are referred to as Intensive sessions, whose sole objective is the measurement of dUT1 (Nothnagel and Schnell, 2008).

Intensive sessions, however, pose some limitations in VLBI analysis compared to a multi-station network because of their one-baseline geometry:

- Because the baseline has to be very long, the resulting sky coverage is poor, as there are only few sources visible by both antennas (Teke et al., 2015).
- It is impossible to estimate polar motion, nutation as well the TRF and CRF from one baseline (Nothnagel and Schnell, 2008).
- Horizontal gradients cannot be estimated with sufficient accuracy (Böhm et al., 2010).

In the last few years, great efforts have been made to make the estimated dUT1 values from Intensive sessions more accurate. Some papers deal with the selection of appropriate sources (Uunila et al., 2012; Gipson and Baver, 2016), while others address suitable selection of station geometry or observation length. Artz et al. (2012), for instance, came to the conclusion that extending the observation length from 1 h to 2 h would be associated with a decrease of formal errors by a factor of $\sqrt{2}$. Kareinen et al. (2017), on the other hand, found that adding a third station to the schedule in tag-along mode would improve dUT1 estimates by up to 67%, depending on the selected location.

Minimizing the delay between observation and availability of the estimated dUT1 has also been a major topic throughout the last years. According to Koyama et al. (2008), it is very important to shorten the processing time delay as the accuracy of a dUT1 value deteriorates with time. In earlier times, the observed VLBI data had been shipped on disks to the correlation center, resulting in a latency of a couple of days. In the 00s, the latency has been shortened tremendously due to the use of electronic transfer (Luzum and Nothnagel, 2010). Nowadays it is possible to determine dUT1 with a latency of less than 5 min after the end of a session by combining real-time data transfer, near-real-time data conversion and correlation, together with near-real-time data analysis (Haas et al., 2010). Koyama et al. (2008) managed to estimate dUT1 within 3:45 min after an Intensive e-VLBI session between Onsala and Tsukuba. Moreover, Haas et al. (2010) found an indication that higher data rates lead to reduced formal uncertainties in the dUT1 results.

Particularly important for this paper are the works by Böhm et al. (2010), Nafisi et al. (2012) and Teke et al. (2015), all of which are dedicated to improving dUT1 estimates by means of introducing external information on azimuthal asymmetry to the VLBI analysis. Böhm et al. (2010) applied direct ray-tracing through Numerical Weather Models (NWMs) at the station TSUKUB32, which turned out to slightly improve dUT1 estimated in VLBI analysis. Nafisi et al. (2012) validated the quality of their ray-traced delays by means of comparing the resulting VLBI dUT1 to LODs from GNSS, thus achieving a reduction in standard deviation by 4.5%. Teke et al. (2015) utilized horizontal gradients from GNSS analysis from the Center for Orbit determination (CODE) to describe the lack of information on azimuthal asymmetry. Thus, they derived LOD values from the dUT1 estimates which have a better agreement with LODs from GNSS than without using the a priori gradients.

In this study, we apply state-of-the-art gradient models and ray-traced delays from the powerful VieVS ray-tracer (also referred to as RADIATE) (Hofmeister and Böhm, 2017), which are freely available in real-time as well as for all VLBI observations since 1980 on the VMF server by TU Wien at http://vmf.geo.tuwien.ac.at. The intention is on the one hand to confirm the hypothesis that external information on azimuthal asymmetry improves dUT1 estimates, but on the other hand also to attain higher improvements through the new gradient models and ray-traced delays.

2. VLBI analysis of the Intensive sessions

There are different types of VLBI Intensives: The hour-long INT1 (or XU) sessions observe from Monday to Friday at 18:30 UTC on the baseline WETTZELL - KOKEE, while the INT2 (or XK) sessions measure on the baseline WETTZELL - TSUKUB32 on weekends at 07:30 UTC (Fig. 1). Additionally, in order to fill the gap between Sunday 07:30 and Monday 18:30, INT3 (also XU) sessions were launched in 2007 scheduled for Mondays at 07:00 UTC between stations WETTZELL, TSUKUB32 and NYALES20. For the sake of completeness it should be noted that from time to time different baselines than those depicted in Fig. 1 observe the Intensives, which is due to maintenance activities at the stations. For our analysis, however, we considered only the “standard” baselines as outlined in the figure. In the observed period of 2013–2017, they represent 83% of the INT1 sessions (926 of 1116) and 75% of the INT2 sessions (334 of 447).

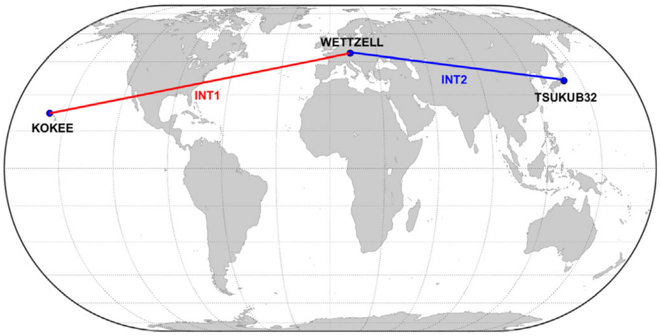

Fig. 1. Geometry of the INT1(XU) baseline WETTZELL-KOKEE, extending over 12,000 km, and the INT2 (XK) baseline WETTZELL-TSUKUB32 with a length of more than 9000 km, which was established 10 years after INT1 owing to the importance of a regular and dense monitoring of dUT1. Both baselines represent a best possible east-west extension.

All VLBI analyses depicted in the following sections were carried out using the Vienna VLBI and Satellite Software VieVS (Böhm et al., 2018).

The initial task for the VLBI analysis was to define input models and settings. We followed the IERS conventions (Petit and Luzum, 2010) for this purpose. First, the reference frames were set to ITRF2014 (Altamimi et al., 2016) and ICRF2 (Fey et al., 2015). ITRF2014 models the post-seismic deformation effects in the wake of the 2011 Japan earthquake, which is important for INT2 (containing Japanese station TSUKUB32). The a priori EOPs come from the IERS EOP 14 C04 series (Bizouard et al., 2017), which comply with the IAU 2006/2000 precession/nutation model. For ocean tidal effects on Earth rotation, we applied the combined GPS/VLBI solution by Artz et al. (2011). According to Scherneck and Haas (1999), the application of accurate ocean tidal loading corrections is particularly important because deficiencies in these models can easily cause errors of several µs. For the troposphere correction, the Vienna Mapping Functions 3 (VMF3) (Landskron and Böhm, 2017) were used, although the influence of errors in the mapping functions on the dUT1 estimates are rather small, as they mainly effect the height component of the stations (Böhm and Schuh, 2007).

Unlike mapping functions, horizontal gradients have a significant influence on dUT1. This holds particularly for the east gradient G_e, as the dUT1 estimate is roughly dependent on the sum of total east gradients over all stations (Böhm and Schuh, 2007). However, there is no chance to estimate the gradients with sufficient accuracy from one-baseline observations (see Section 1), which causes a significant contribution of some tens of µs to the estimated dUT1 (Böhm et al., 2010). Appropriate a priori models can potentially remedy the lack of information on azimuthal asymmetry. Ray-traced delays contain information about the azimuthal anisotropy of a received signal, too. The VieVS ray-tracer performs 2D piecewise-linear ray-tracing through six-hourly $1^\circ \times 1^\circ$ Operational analysis NWMs by the European Center for Medium-range Weather Forecasts (ECMWF) and thus can determine troposphere delays for any elevation and azimuth.

As described in the introduction, many parameters, which are commonly estimated in VLBI analysis, cannot be estimated from Intensive sessions. In fact, the estimation outputs only the following quantities:

- one linear function to describe the clock difference between the stations,
- two zenith wet delays (one at each station) per session,
- one dUT1 offset (= ΔdUT1) with respect to the a priori EOP 14 C04 per session (yielding values in the range of some tens of µs).

All other parameters are fixed to their a priori values.

In view of the small number of estimated parameters, a priori information about azimuthal asymmetry is of particular importance. Therefore, we set up four approaches as outlined in Table 1. The first approach does not include any information about azimuthal asymmetry. Approaches 2 and 3 apply empirical gradients from the empirical troposphere model GPT3 and the discrete horizontal gradients GRAD, respectively, both published in Landskron and Böhm (2018). The terms *discrete* and *empirical* are understood as such as discrete models directly adopt information from ray-tracing through NWMs at certain times and locations, while empirical models rely on experience values from climatology. Eventually, in approach 4 we utilize ray-traced delays for all observations of the Intensive sessions in the given time interval.

Now the aim of the investigation is to find out, whether and to which extent the approaches 2, 3 and 4 of Table 1 may improve the estimates.

The analysis comprises two comparisons in two different time frames with different reference values regarded as the "true" values each:

1. ΔdUT1 (the additions to the a priori values) estimated from INT1 sessions compared to ΔdUT1 from regular multi-station VLBI sessions during the Continuous VLBI Campaign 2017 (CONT17). (Since there were only 4 INT2 sessions during CONT17, these were not considered). In multi-station VLBI sessions, all five EOPs plus several further important parameters such as horizontal tropospheric gradients are estimated. As a consequence, very high accuracy can be attributed to the resulting dUT1.

Table 1
Naming and description of the various approaches done in the comparison.

APPROACH	DESCRIPTION
(1) No grad	No a priori values for azimuthal asymmetry
(2) GPT3 grad	Application of empirical a priori gradients from GPT3
(3) GRAD grad	Application of discrete a priori gradients from GRAD
(4) Ray-traced	Application of ray-traced delays

2. LOD determinations inferred from estimates of dUT1 from INT1 and INT2 sessions compared to LOD from GNSS by CODE (Dach et al., 2009) in the period of 2013–2017. The GNSS LODs are very accurate owing to their wealth of data, making them worth being used as reference values as well.

In theory, each estimated ΔdUT1 value is valid during the whole observation interval of the respective session. However, for quantification we set the validity of each value to the middle of its observation interval, which is 19:00 (UT) for INT1, 08:00 for INT2 and 12:00 for XA as well as XB sessions. Linear interpolation between the epochs facilitates to compare the different sessions with each other.

LOD, which is the deviation of the day length from 86400 s, can only be obtained indirectly with VLBI. Eq. (1) outlines how to derive LOD from two dUT1 values of consecutive days t_1 and t_2. It is generally represented in $\frac{\mu s}{day}$.

$$LOD(t_{1.5}) = \frac{dUT1(t_2) - dUT1(t_1)}{t_2 - t_1} \quad (1)$$

The resulting LOD value is then valid between the two surrounding dUT1 measurements, that is, the INT1 LODs are valid at 07:00 and the INT2 LODs at 20:00. Since only immediately consecutive days can be considered, the resulting LOD epochs represent only 55% of the dUT1 epochs of INT1. For INT2, even only 45% of the dUT1 epochs remain.

To ensure highest possible data quality, a set of outlier reductions was carried out. First, all dUT1 estimates from VieVS with a formal error σ of more than 25 µs were excluded. Next, a simple 3σ outlier rejection was carried out. Eventually, all estimated LODs which are more than 80 µs away from the reference GNSS LODs were regarded as outliers as well. After all limitations and exclusions, 660 INT1 and 323 INT2 sessions remained for the period of 2013–2017. In case of CONT17, 9 of 11 INT1 sessions successfully passed the outliers rejections.

3. Results

The results of the dUT1 estimates and LOD determinations inferred from the dUT1 estimates are validated by means of comparisons with reference values. In the following, we differentiate between the two comparisons outlined in Section 2.

For the sake of completeness it is mentioned that all analyses except for that of the INT2 sessions in Section 3.2 is based on VLBI data in the new vgosDB data format. For the INT2 sessions this was not possible though, thus NGS data files were used instead.

3.1. Comparison of dUT1

Continuous VLBI experiments, which are carried out triennially since 2002, are particularly suited for estimating parameters such as dUT1 for testing or comparing purposes. In the 2017 experiment, CONT17, which ran from November 28 through December 12, two independent legacy networks observed: the XA sessions contain the 10 VLBA stations in North America plus 4 additional IVS stations in Europe and Australia, while XB sessions consist of 14 different VLBI stations all over the world.

Fig. 2 shows estimates for ΔdUT1 from Intensives and from multi-station sessions. The difference between the two reference ΔdUT1 series XA and XB themselves appears to be in the same range as the difference between any reference ΔdUT1 series and the ones from the Intensives.

Tables 2 and 3 summarize the differences between the four approaches and the reference values, averaged over all epochs. The bias represents the mean over all differences

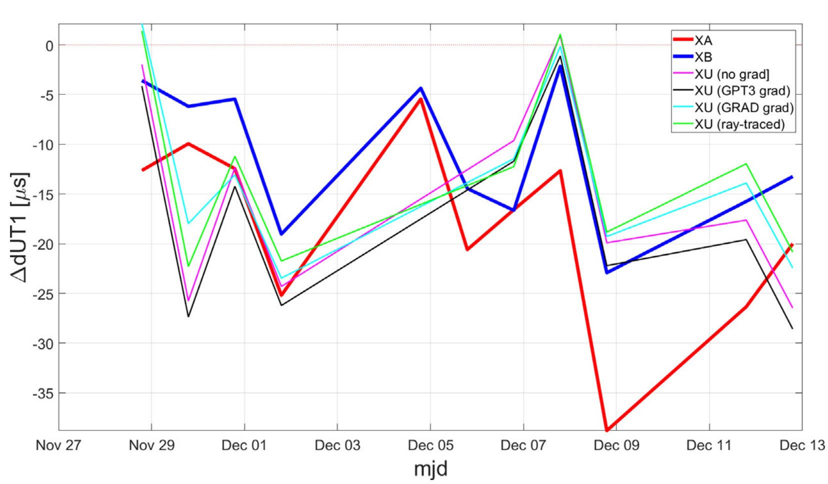

Fig. 2. ΔdUT1 estimated from VLBI analysis using VieVS from multi-station sessions and from INT1 (XU) Intensive sessions for the time period of CONT17. The mean formal error of the estimation is lowest for XA sessions (1.1 µs ± 0.1 µs), higher for XB sessions (2.3 µs ± 0.6 µs) and significantly higher for the Intensive sessions (∼13 µs ± 6.4 µs). The latter is a consequence of the lower number of observations of Intensive sessions.

Table 2
Mean absolute error (first column), bias (second column) and standard deviation (third column) of ΔdUT1 (μs) between (reference) XA sessions and INT1 session using different a priori settings, averaged over the 15 days of CONT17.

Approach	MAE ΔdUT1	Bias ΔdUT1	σΔdUT1
No grad	9.1	−4.2	10.7
GPT3 grad	8.6	−2.2	10.5
GRAD grad	8.6	−6.1	9.2
Ray-traced	9.4	−6.4	10.0

Table 3
Mean absolute error (first column), bias (second column) and standard deviation (third column) of ΔdUT1 (μs) between (reference) XB sessions and INT1 sessions using different a priori settings, averaged over the 15 days of CONT17.

Approach	MAE ΔdUT1	Bias ΔdUT1	σΔdUT1
No grad	6.8	3.6	8.6
GPT3 grad	7.1	5.6	8.5
GRAD grad	5.7	1.6	6.7
Ray-traced	5.9	1.3	7.3

$XA/XB - XU$, while the mean absolute error (MAE) gives the mean of all absolute differences $|XA/XB - XU|$. Overall, the results of Tables 2 and 3 suggest that a priori information on azimuthal asymmetry has a positive effect on the dUT1 estimates. Using a priori gradients GRAD improves the estimates by about 5% in MAE when compared to XA sessions and 16% in MAE when compared to XB sessions. However, ray-traced delays tend to deteriorate the estimates by 3% when compared to XA sessions but improve the estimates by 13% when compared to XB sessions. Regarding the empirical gradients GPT3, there is no clear message whether they improve or deteriorate the results. Interestingly, the MAE between the two reference values XA and XB is 7.0 μs, which is in the range of the MAE of Tables 2 and 3. Fig. 2 proves that the difference between XA and XB is a clear bias. Thus, on the one hand, ΔdUT1 from XA and XB sessions do not appear to be appropriate and trustworthy reference values. But on the other hand, this also means that the quality of dUT1 from Intensives is fairly good, given the fact that they contain not even 1% of the observations of multi-station sessions (during CONT17, the average number of observations of XA and XB sessions is 4975 and 5396, respectively, while XU sessions consist of only 37 observations).

In any case, a longer time span and consequently a larger data set is necessary.

3.2. Comparison of LOD

While the CONT17 comparison consists of only 9 epochs, the LOD comparison for the period of 2013 through 2017 is considerably more extensive, containing 378 INT1 epochs and 148 INT2 epochs, making the results significantly more meaningful. The reference values here are GNSS LODs estimated by CODE analysis center. The VLBI estimates first had to be interpolated to the exact times of the GNSS LODs, which was accomplished through spline interpolation. Comparisons to LODs from GNSS were already made by Böhm et al. (2010), Nafisi et al. (2012) as well as by Teke et al. (2015).

Fig. 3 outlines the comparison of the LODs from VLBI analysis of INT1 Intensive sessions with the GNSS ones. The VLBI LODs generally go well with the GNSS LODs. However, the differences between the VLBI approaches are too small to see any systematics. Fig. 4 therefore displays the differences between GNSS LODs and the VLBI LODs from INT1 and INT2 sessions (=ΔLOD) for a shorter time interval.

Averaging the ΔLODs over the full time period of 2013–2017 yields Tables 4 and 5, outlining the statistics for INT1 and INT2, respectively. In general, this confirms the results of the dUT1 comparison in Section 3.1, albeit to a lesser degree. By applying the discrete a priori gradients GRAD

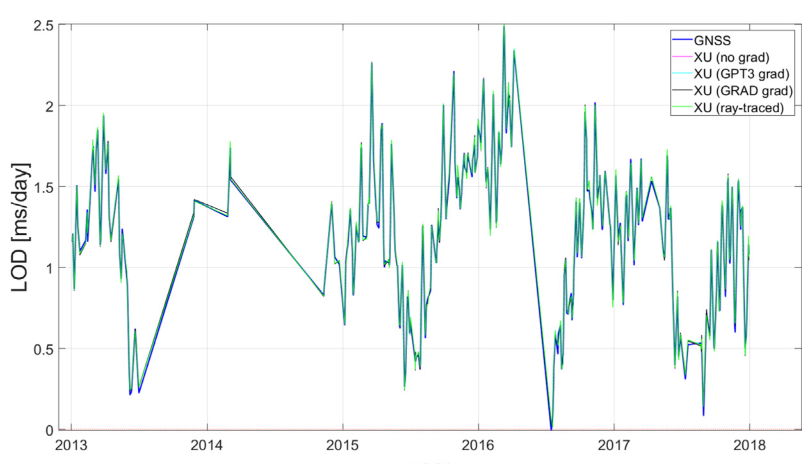

Fig. 3. LOD from GNSS analysis by CODE (blue) and from VLBI analysis of INT1 (XU) sessions using different a priori settings for the time period of 2013–2017. There are some data gaps because of the VLBI data, especially in 2014, where a different VLBI network was measuring INT1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

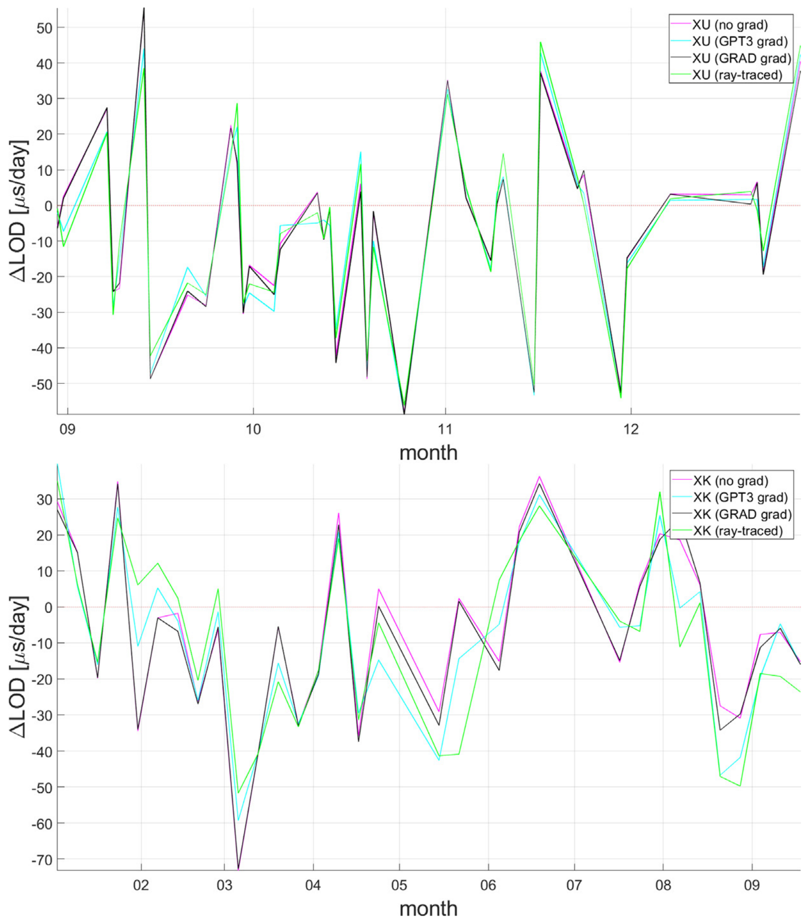

Fig. 4. Difference in LOD between GNSS LOD and those from VLBI analysis of INT1 (XU) sessions using different a priori settings, for visibility limited to some months in 2016.

or ray-traced delays, the resulting LODs can be improved by about 7% for INT1 and by about 4% for INT2 sessions. Applying empirical a priori gradients from GPT3 does not necessarily enhance the estimates, in case of INT2 it even slightly deteriorates them by 2%. What is also conspicuous is that all LODs estimated from Intensive sessions are systematically larger in magnitude than the reference values, thus always causing a negative bias. The reason for this might be deficiencies in GNSS orbit modeling.

Table 4
Mean absolute error (first column), bias (second column) and standard deviation (third column) of ΔLOD (μs/day) between (reference) GNSS and INT1 sessions using different a priori settings, averaged over the five years of 2013 through 2017.

Approach	MAE ΔLOD	Bias ΔLOD	$\sigma\Delta$LOD
No grad	21.3	−7.4	25.9
GPT3 grad	21.4	−7.5	25.9
GRAD grad	19.9	−7.6	24.1
Ray-traced	19.9	−7.4	24.1

Table 5
Mean absolute error (first column), bias (second column) and standard deviation (third column) of ΔLOD (μs/day) between (reference) GNSS and INT2 sessions using different a priori settings, averaged over the five years of 2013 through 2017.

Approach	MAE ΔLOD	Bias ΔLOD	$\sigma\Delta$LOD
No grad	22.7	−9.8	26.1
GPT3 grad	23.2	−10.2	26.6
GRAD grad	21.8	−9.7	25.6
Ray-traced	21.9	−8.7	25.7

4. Conclusions

In this paper, we estimated the effect of a priori information on azimuthal asymmetry from external sources on the Earth rotation angle dUT1 and on length-of-day LOD as estimated from Intensive VLBI sessions on two different baselines. By means of comparison with dUT1 estimated from multi-station VLBI sessions, we were able to detect an improvement in MAE of up to 16% when applying the discrete a priori gradients GRAD and up to 13% when using ray-traced delays. However, it turned out that dUT1 from multi-station sessions may not be an appropriate reference value for assessing the quality of dUT1 from Intensives. In a second, more extensive comparison, we converted the estimated dUT1 to LOD and compared these to LOD values estimated from global GNSS analyses. Thus, we could determine an improvement in MAE of

4–7% when applying GRAD or ray-traced delays. In conclusion it can be said that a priori information on azimuthal asymmetry is of considerable importance for Intensive VLBI sessions, as it compensates a part of the information loss resulting from the lack of estimated parameters. The performance of GRAD and ray-traced delays is fairly equal, however slightly better for GRAD, which is why we promote using them for Intensive sessions. The general conclusions of the works by Böhm et al. (2010), Nafisi et al. (2012) and Teke et al. (2015) are confirmed, although the improvements achieved in this paper with the state-of-the-art model GRAD and the ray-traced delays by the VieVS ray-tracer are distinctly larger. All gradient models and ray-traced delays are freely available at http://vmf.geo.tuwien.ac.at.

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