Nilsson, T., Soja, B., Balidakis, K., Karbon, M., Heinkelmann, R., Deng, Z., Schuh, H. (2017): Improving the modeling of the atmospheric delay in the data analysis of the Intensive VLBI sessions and the impact on the UT1 estimates. - *Journal of Geodesy*, *91*, 7, pp. 857—866.

DOI: http://doi.org/10.1007/s00190-016-0985-7

manuscript No.
(will be inserted by the editor)

Improving the modeling of the atmospheric delay in the data analysis of the Intensive VLBI sessions and the impact on the UT1 estimates

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Received: date / Accepted: date

This work was supported by the Austrian Science Fund (FWF), project number P24187-N21 (VLBI-ART).

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Abstract The VLBI (very long baseline interferometry) Intensive sessions are typically 1-hour and single-baseline VLBI sessions, specifically designed to yield low-latency estimates of UT1-UTC. In this work, we investigate what accuracy is obtained from these sessions and how it can be improved. In particular, we study the modeling of the troposphere in the data analysis. The impact of including external information on the zenith wet delays (ZWD) and tropospheric gradients from GPS or numerical weather prediction models is studied. Additionally, we test estimating tropospheric gradients in the data analysis, which is normally not done. To evaluate the results we compared the UT1-UTC values from the Intensives to those from simultaneous 24-h VLBI session. Furthermore, we calculated Length of Day (LOD) estimates using the UT1-UTC values from consecutive Intensives and compared these to the LOD estimated by GPS. We find that there is not much benefit in using external ZWD, however, including external information on the gradients improves the agreement with the reference data. If gradients are estimated in the data analysis, and appropriate constraints are applied, the WRMS difference w.r.t. UT1-UTC from 24-h sessions is reduced by 5 % and the WRMS difference w.r.t. the LOD from GPS by up to 12 %. The best agreement between Intensives and the reference time series are obtained when using both external gradients from GPS and additionally estimating gradients in the data analysis.

Keywords VLBI, Intensives, Universal time 1, Length of day, Kalman filter, Troposphere, Tropospheric gradients

1 Introduction

Very long baseline interferometry (VLBI) is one of the main techniques for measuring the Earth orientation parameters (EOPs). In particular, VLBI is the only technique capable of determining Universal Time (UT1-UTC) and precision/nutation. Coordinated by the International VLBI Service for Geodesy and Astrometry (IVS, Schuh and Behrend, 2012), two so-called rapid turnaround (IVS-R1 and IVS-R4) 24-h VLBI sessions are observed every week, with the main purpose being to estimate the EOPs. For logistic reasons, the results from these sessions are typically available with a latency of about two weeks. It is, however, for many applications desirable to have the results available with lower latency and with higher time resolution. In order to provide this for UT1-UTC, special 1-hour VLBI sessions, so-called Intensives (Robertson et al., 1985), are observed every day. Typically these sessions are observed with just two stations on a long East-West baseline (needed to have good sensitivity to UT1-UTC). The results are typically available within two days.

Currently, mainly three different types of Intensives are observed within the IVS, see Fig. 1. On weekdays, between 18:30 UT and 19:30 UT, the INT1 sessions are observed with the stations Wettzell (Germany) and Kokee Park (Hawaii, USA). Sometimes, also the station Svetloe (Russia) participates in these sessions. On weekends, between 07:30 UT and 08:30 UT, the INT2 sessions are observed with Wettzell and Tsukuba (Japan). Additionally, the INT3 sessions are observed on Mondays between 07:00 UT and 08:00 UT, using the three stations Wettzell, Tsukuba, and Ny-Ålesund (Spitsbergen, Norway) (Luzum and Nothnagel, 2010). Occasionally, when one of the original stations used in the Intensives has been unavailable due to, e.g. a repair of the antenna, another station has been used instead. Additionally, there are a few Intensives series observed outside the framework of the IVS, i.e, in Russia and the USA. In this paper, we only investigate the IVS Intensives and, unless otherwise noted, we will for consistency use the designation INT1 to denote only those Intensives observed with the baseline Wettzell–Kokee and INT2 to denote only the sessions observed with Wettzell–Tsukuba.

The accuracy of the results obtained from the Intensives are, however, limited for a number of reasons. First of all, since typically the observations are made with just a single baseline and the sessions are just 1 hour long, it is impossible to use the same parametrization of the Earth orientation as in the processing a standard 24-h VLBI session (offsets for all five EOP, and rates for polar motion and UT1-UTC), without imposing strong constraints. In principle, it is only possible to estimate two parameters describing the orientation since the observations are insensitive to any rotation around the baseline and 1 hour is too short to properly separate polar motion and precession/nutation. Secondly, since the sessions are only one hour long, the number of observations are limited. Normally, only 20–40 observations are made in an Intensive (about 20 in an INT1 session and 30–40 in an INT2). Furthermore, the geometrical distribution of the radio sources is not optimal since a very long baseline (8000–10000 km) is used, and the radio sources need to be visible from both stations. Because of these reasons, the number of parameters that can be estimated in the data analysis of an Intensive session is limited. Typically, only one clock polynomial (offset, rate, and sometimes also a quadratic term), one constant zenith wet delay (ZWD) per station, as well as one UT1-UTC offset are estimated. Other parameters, such as polar motion, celestial pole offsets, station coordinates, and tropospheric gradients, are fixed to their a priori values. Thus, any unmodeled errors in these a priori values could cause errors in the estimates of UT1-UTC (and other parameters).

Since the Intensives is the only source of low-latency UT1-UTC currently existing, there is a desire to improve the accuracy. This is important for all applications needing low-latency UT1-UTC information, e.g. satellite and space craft navigation. In several works different ways of improving the accuracy have been investigated. For example, Gipson and Baver (2016) investigated the effect of applying two different strategies when scheduling the sessions, Nothnagel and Schnell (2008) and Malkin (2011) investigate the effect of the a priori polar motion and celestial pole offsets used in the data analysis, and Malkin (2013) studied the impact of neglecting the seasonal station motions in the data analysis.

The neutral atmosphere is one of the largest error sources for geodetic VLBI (Nilsson and Haas, 2010). Normally, the atmospheric delay, ℓ_{atm}, is modeled in the VLBI data analysis by the following expression (e.g., Nilsson et al., 2013):

$$\ell_{atm} = m_h(\epsilon)\,\ell_h^z + m_w(\epsilon)\,\ell_w^z + m_g(\epsilon)\,[G_n\,\cos a + G_e\,\sin a] \tag{1}$$

where ℓ_h^z and ℓ_w^z denote the zenith hydrostatic delay (ZHD) and ZWD, respectively, m_h and m_w are the hydrostatic and wet mapping functions, respectively (e.g., Böhm et al., 2006), m_g is the gradient mapping function (e.g., Chen and Herring, 1997), G_n and G_e are the tropospheric gradients in the north and east directions, respectively, ϵ is the elevation angle, and a the azimuth angle of the observation. The first two terms on the right-hand side of Eq. (1) describe the a part of the atmospheric delay independent of the azimuth angle, while azimuthal dependence is taken into account by the third term (to the first order approximation). More specifically, the third term describes the delay caused by linear horizontal variations in the refractive index above the site, or, equivalently, by tilting of the mapping function (see e.g. Nilsson et al. 2013 for details). The ZHD can be accurately determined from surface pressure measurements (Davis et al., 1985), and accurate expressions for the mapping functions exist. However, due to the fact that water vapor is highly volatile in both space and time accurate values of the ZWD, as well as G_n and G_e, are not easily obtainable, hence these are typically estimated (as piece-wise linear functions) in the data analysis of standard 24-h VLBI sessions. In the data analysis of Intensives, however, only the ZWD (as a constant value over the whole session) is estimated while the gradients are normally fixed to the prediction of a simple empirical model (or even to zero). Such empirical models can induce significant errors since they do not model the rapid variations in the gradients on timescales from hours to days, but normally only the climatological mean over several years. This will propagate into errors of the parameters estimated in the data analysis, such as UT1-UTC. For example, if there is a common error in the a priori East gradient of 1 mm, which is not unrealistic, this will cause a UT1-UTC error of 20–30 μas (Nilsson et al., 2011, 2014).

Böhm et al. (2010) performed tests using ray-traced delays, as well as a priori gradients calculated from ECMWF data, in the analysis of the INT2 sessions. They compared the Length of Day (LOD) estimated from consecutive Intensives with the estimates from a GNSS (Global Navigation Satellite Systems) solution. A slight improvement was found using the ray-traced delays, but no improvement when using ECMWF gradients. Teke et al. (2015) used gradients and ZWD estimated from GNSS data in the analysis of the Intensive sessions and found an improvement in the agreement between LOD estimated from sequential Intensives and those estimated from GNSS when doing so. Another approach for handling the gradients is to estimate them in the data analysis, as suggested by Nilsson et al. (2011). This is possible if they are tightly constrained to their a priori values. As shown by Nilsson et al. (2011) and Nilsson et al. (2014) this can improve the agreement of UT1-UTC estimated from the Intensives with those estimated from 24-h VLBI sessions.

In this work, we investigate the accuracy of the UT1-UTC estimates from the Intensives and ways to improve it. In particular, we focus on how to handle the errors introduced by the atmosphere. We further evaluate the possibility of estimating gradients in the data analysis and derive the optimal levels of the constraints needed to be applied to these. Furthermore, we study the possibility to use tropospheric gradients and ZWD from GPS. Here, we do not only test the effect of using the GPS estimates as a priori values, but also the possibility to include them as additional observations in the data analysis. We apply two methods of validating the results. The first is a direct comparison with the UT1-UTC estimated from simultaneous 24-h VLBI sessions. The second method is an indirect validation of the UT1-UTC estimates from the Intensives by first estimating the LOD using UT1-UTC from two consecutive Intensive sessions and then comparing these values to with the LOD values estimated from GPS.

2 Data analysis

We have analyzed all Intensive sessions from the period 2002–2015, in total 4428 sessions, with the GFZ version of the Vienna VLBI Software (Böhm et al., 2012), VieVS@GFZ (Nilsson et al., 2015; Soja et al., 2015). The a priori modeling basically follows the IERS 2010 Conventions (Petit and Luzum, 2010), except that we also corrected for non-tidal atmospheric loading (Petrov and Boy, 2004). For the modeling of the atmospheric delays we applied the Vienna Mapping Functions (VMF1, Böhm et al., 2006) and the gradient mapping function of Chen and Herring (1997). The a priori gradients were obtained from the static a priori gradient (APG) model (Böhm et al., 2013), which provides the climatological mean gradient based on ECMWF operational analysis data. The a priori station and radio source coordinates were taken from the ITRF2014[1] and ICRF2 (Fey et al., 2015) catalogs, respectively, while the a priori EOP were taken from the USNO finals series[2].

For the parameter estimation, we used the Kalman filter module of VieVS@GFZ, VIE_KAL. In the standard analysis, we estimated clock parameters modeled as random walk processes, constant ZWD for each station, and a constant UT1-UTC offset. Between the sessions, the ZWD and UT1-UTC were modeled as random walk processes with Power Spectral Densities (PSD) of 58 cm^2/day and 1 ms^2/day, respectively, while the clocks were completely reset at the beginning of each session.

2.1 GPS analysis

In the study, we have tested using tropospheric parameters from GPS in the data analysis of the Intensives. We used GPS data from the three main Intensive stations: Wettzell (GPS station WTZR), Kokee (KOKB) and Tsukuba (TSKB). The GPS data from these stations and from the period 2002–2015 were analyzed with

[1] `http://itrf.ign.fr/ITRF_solutions/2014/`
[2] `ftp://maia.usno.navy.mil/ser7/finals.daily`

GFZ's GNSS analysis software package, Earth Parameter and Orbit determination System (EPOS) (Deng et al., 2016). The station parameters were estimated using the precise point positioning (PPP) model. In the processing, the GPS orbits and clocks were fixed to those from the 2nd IGS TIGA (Tide Gauge Benchmark Monitoring) reprocessing and the GFZ routine IGS final products. The station-related parameters were estimated based on least-squares adjustment: station positions with daily resolution, receiver clocks for every epoch, zenith total delays with 30 min resolution, and tropospheric gradients with hourly resolution.

2.2 ERA-Interim gradients

The tropospheric gradients can also be calculated from the meteorological data provided by numerical weather prediction models (NWM). In a NWM, the asymmetric features of the troposphere are simulated by humidity and temperature gradients, which are related to the gradients in the refractivity field. Thus, tropospheric gradients can be estimated by slant delays obtained by ray-tracing through the refractivity fields.

For our investigations we employ data from the meso-beta scale NWM ERA-Interim reanalysis (Dee et al., 2011), which is the latest ECMWF re-analysis, at the original resolution (6-hourly $1^\circ \times 1^\circ$ fields on 60 model levels). We utilize the 3D fields of temperature and specific humidity as well as the surface fields of pressure and geopotential in order to calculate the 3D fields of partial pressure for dry air and for water vapor, and therefore the hydrostatic and non-hydrostatic refractivity fields (Thayer, 1974). Following Zus et al. (2012) and Zus et al. (2014), 120 azimuth-dependent and azimuth-independent slant delays (the azimuthal spacing is set to 30°, and the elevation angles are $\epsilon = [3\ 5\ 7\ 10\ 15\ 20\ 30\ 50\ 70\ 90]^{\circ}$) are computed for each station by multiplying the zenith delays with the mapping factors (obtained by true direct mapping) for the hydrostatic and non-hydrostatic component separately. Afterwards, the North-South and East-West gradient components are estimated by least-squares fitting of the product of their differences with the gradient mapping function (Chen and Herring, 1997).

2.3 Reference solution

To validate our results from the Intensives, we used the UT1-UTC estimates from simultaneous standard 24-h VLBI sessions. These values provide an excellent reference since they have an accuracy of about 5 μs, which is significantly better than the accuracy of the Intensives (15–20 μs). In total, we used 1216 IVS-R1, IVS-R4, and CONT sessions between 2002–2015 for this purpose, out of which 1088 sessions were simultaneous to an INT1. These sessions were also analyzed with VieVS@GFZ, applying the same a priori modeling as for the Intensives. The parameter estimation was performed with the classical least-squares module, VIE_LSM. The parameter estimation was similar to what is described in Heinkelmann et al. (2014). For all EOP, we estimated offsets, and for polar motion and UT1-UTC additionally rates. The UT1-UTC offsets and rates were then used to calculate the reference values at the epochs of the Intensive sessions.

However, as normal 24-h VLBI sessions are typically not observed on weekends, we need an alternative way to evaluate the results of the INT2 sessions. Comparing against a combined EOP series such as the USNO finals is not a reliable metric since the results from the Intensives are assimilated in these combinations and therefore such series cannot be considered independent. Thus, we decided to do the evaluation indirectly using the LOD, i.e. the negative time derivative of UT1-UTC, since accurate LOD are available for every day from GPS. Of course, one Intensive session is too short (1 h) to get reliable LOD estimates. However, we can calculate an estimate of the mean LOD between two Intensives as the difference between the UT1-UTC estimates divided by the time difference, similar to what was done in, e.g., Böhm et al. (2010) and Teke et al. (2015). Since these LOD values are directly calculated from the UT1-UTC estimates, they can be used as an indirect way to evaluate the UT1-UTC accuracy. This method also has the advantage that it is more or less independent of VLBI. However, it should be noted that the LOD derived in this way will mostly be sensitive to the random errors in the UT1-UTC estimates which are uncorrelated between two Intensive sessions, while slowly varying systematic errors in UT1-UTC cannot be detected.

For the calculation of the LOD values from the Intensives we used all pairs of Intensive sessions where the time difference between the sessions was less than 1.2 days, and the effects of zonal tides were removed before the calculations using the model in the IERS 2010 Conventions (Petit and Luzum, 2010). In total, we obtained 1752 LOD values from the INT1 sessions and 480 values for the INT2 sessions. As a reference to these estimates, we used the LOD from the IGS (International GNSS Service) final solution (Dow et al., 2009). These LOD values have an accuracy of about 10 μs, which is better than what we expect from the Intensives (20–30 μs). From the IGS time series, we first removed the effect of zonal tides, then we calculated the mean LOD value for each period for which we have calculated LOD from the Intensives. It should be noted that the obtained reference LOD series might not be totally consistent with the LOD from the Intensives, e.g., due to slight differences in the handling of the LOD rate, however, we expect these effects to be small and should not have any major impact on our results.

3 Results

3.1 Kalman filter and least-squares solutions

We first compared the Kalman filter solution described in Sec. 2 to a solution calculated with the classical least-squares (LSM) module of VieVS@GFZ, as well as to a Kalman filter solution where each session was analyzed individually (i.e., without any constraints on the variability of ZWD and UT1-UTC between the sessions). Table 1 shows the weighted mean (WM) and weighted root-mean-square (WRMS) differences between the Intensive solutions and the reference solution calculated from the 24-h VLBI sessions. We observe that the WRMS values are lower for the Kalman filter solutions, and lowest for the solution where the variability is constrained between the sessions. Similar results are obtained if we look at the LOD differences. The differences mostly come from Intensive sessions with low sensitivity to UT1-UTC. Since the Kalman filter needs to be initialized with initial values of the parameters and their variance-covariance matrix, the solution will be loosely constrained to these values. Applying constraints between the sessions imposes further restrictions on the solution. This prevents the estimates from differing too much w.r.t. the a priori values, which could happen should the UT1-UTC sensitivity be low. For the LSM solution, we did not apply any absolute constraints to the parameters, hence slightly larger WRMS values were obtained.

3.2 Multi-baseline Intensives

We made a test of the impact of having more than three stations observing an Intensive. For this, we looked at the INT1 sessions which include Svetloe (65 sessions), as well as the INT3 sessions (149 sessions). We calculated a Kalman filter solution where all observations including Svetloe or Ny-Ålesund were excluded from these sessions, and compared the results to the original solution where these stations were included. To get a reference for the INT3 sessions, we extrapolated the UT1-UTC estimates from the 24-h sessions (for all other investigations in this work, no extrapolation was performed, only interpolation). We find that the UT1-UTC WRMS differences relative to the reference series increase when excluding the extra stations: for the INT1 sessions with Svetloe from 20.6 μs to 21.2 μs, and for the INT3 sessions from 29.0 μs to 30.1 μs. This indicates that the extra station improves the precision of the UT1-UTC estimates, as expected, although it should be noted that the changes in WRMS differences are not statistically significant (based on a F-test of equal variance).

3.3 ZWD from GPS

If the ZWD could be fixed to accurate a priori values in the data analysis, the number of parameters needed to be estimated would be reduced and thus the precision of the solution (e.g., for UT1-UTC) would get better. The problem is to obtain ZWD with high enough accuracy. One potential source is ZWDs estimated from GPS. To test this possibility, we estimated the ZWDs from the data obtained from the GPS receivers co-located with the Intensive VLBI stations. The data analysis is described in Sec. 2.1. The obtained ZWD values were then corrected for the height difference between the GPS antenna and the VLBI reference point, the so-called tropospheric tie (Teke et al., 2013), and then used as a priori values for the ZWD in a data analysis of the Intensives where the estimation of ZWD was turned off. This, however, made the results worse. For the INT1 sessions, the WRMS UT1-UTC difference relative to the results of the 24 h session increased from 21.6 μs to 24.6 μs. When looking at the LOD results, similar results were found. Here, we only used sessions for which we had GPS data for both stations, in total 3063 sessions, resulting in 846 sessions which could be compared to the reference solution, 1198 LOD values for INT1, and 371 LOD values for INT2.

Even though the GPS ZWDs are not accurate enough so that the ZWD could be fixed to these values, it can still be possible to use these values in the data analysis of the Intensives to improve the solution. One strategy is to include the GPS ZWDs as additional observations instead of using them as a priori values. We also tested this possibility. In the analysis, the uncertainty for the GPS ZWDs were assumed to be given by their formal errors obtained from the GPS analysis. However, in order to further consider the possibility that these formal errors are too optimistic, we calculated solutions where we increased the uncertainties of the GPS ZWDs by multiplying their formal errors by a constant factor. The results for LOD can be seen in Fig. 2. We note that the agreement is improved (although the improvement is not statistically significant) for the INT1 sessions when including the GPS ZWDs with their formal errors multiplied by a factor larger than about 2.7. For factors smaller than 2.7 the results are, however, degraded relative to the case when no GPS ZWDs are included. We obtain similar results when comparing the UT1-UTC estimates to those from the 24-h VLBI sessions. For the INT2 sessions, however, we see practically no improvement when additionally using ZWDs from GPS, only degradation. Both the results for INT1 and INT2 indicate that the GPS formal error factor should be large. The reason for this might be that the formal errors of the GPS ZWDs are too optimistic, although we did not expect this effect to be that large. It is possible that the GPS ZWDs contain systematic errors, or that systematic errors are introduced through the tropospheric ties. For most Intensive sessions, the sensitivity to the ZWD is good, hence external information is not really needed. Thus, if we include external ZWDs which contain systematic errors, this will degrade the solution. Hence, the better results are obtained when we assume large uncertainties of the GPS ZWDs. Only for problematic sessions, where the sensitivity to the ZWD is degraded, do the external data assist in improving the results. This is likely the reason why we only see improvements for the INT1 sessions, since these generally contain fewer observations (20) than the INT2 sessions (30–40), hence if a few observations are lost this has a larger impact for the INT1 sessions.

3.4 Estimation of gradients

As noted by Nilsson et al. (2011), the estimation of gradients from the Intensive sessions is possible, however they must be tightly constrained to their a priori values to avoid getting unreliable results. It is, however, not clear exactly how strong constraints should be applied. To test this, we calculated several solutions where we also estimated gradients in the data analysis of the Intensives. The gradients were modeled as being constant and were reinitialized before every session. Between the different solutions, the a priori standard deviation of the gradients, σ_{Grad}, was varied.

We first assumed the same accuracy for the a priori gradients for all stations. Figure 3 shows the WRMS difference between the UT1-UTC values estimated from the Intensives and those from the simultaneous 24-h VLBI session, as a function of the assumed a priori gradient accuracy. Similarly, Fig. 4 shows the WRMS difference between the LOD estimated from the Intensives and from IGS. We can see that the WRMS difference for both UT1-UTC and LOD decreases when gradients are estimated and the constraints are not too loose especially for the INT2 sessions (Wettzell-Tsukuba). One reason why the INT2 sessions are affected more than the INT1 sessions could be that the higher number of observations and better sky coverage in INT2 enhance the sensitivity to gradients. Another reason is that there are often large gradients present at the Tsukuba station (Teke et al., 2013).

For the INT1 sessions, the optimal value for σ_{Grad} seems to be around 0.6 mm, while for INT2 it is around 0.8 mm. The reduction in WRMS seen when using these values, relative to not estimating gradients, is statistically significant for the INT2 sessions and on the limit of being significant for the INT1 sessions (5 % probability of false detection, based on an F-test). The reason why there is a difference between the optimal σ_{Grad} for the INT1 and INT2 sessions is likely due to the size and variability of the gradients varying between the stations. To obtain the best results, it seems appropriate to use larger σ_{Grad} values for stations with high variability in the gradients than for stations with low variability. Thus, we estimated station-specific values. We did this by calculating several solutions where only σ_{Grad} of one station was varied, while σ_{Grad} of the other stations was fixed to 0.5 mm. We find that the optimal values (those giving the lowest WRMS for UT1-UTC and LOD differences) are 0.8 mm for Kokee and 1.0 mm for Tsukuba. For

Wettzell, we find different values for the two kinds of Intensive sessions: for INT1 0.3 mm and INT2 0.6 mm. The reason for the different results depending on the type of Intensive could be that the INT2 sessions are more sensitive to gradients, thus a larger value for σ_{Grad} can be used. When applying the optimized, station-based σ_{Grad} values, the WRMS differences decrease slightly compared to having the same values for all stations. The LOD WRMS differences are 24.1 μs for INT1 and 19.8 μs for INT2 when optimized station-based values are applied, compared to 24.4 μs and 19.9 μs, respectively, when σ_{Grad} is the same for all stations.

3.5 ERA-Interim Gradients

One possible way of obtaining a priori tropospheric gradients is to calculate them using the output of a NWM. In this work, we have tested using gradients calculated from ERA-Interim (Dee et al., 2011), see Sec. 2.2 for details. If we fix the gradients to these values in the data analysis of the Intensives, the WRMS of the UT1-UTC difference relative to the reference solution marginally decreases from 21.8 μs to 21.4 μs for the INT1 sessions. When looking at the LOD difference between the Intensives and IGS, we also find decreases in the WRMS differences: for the INT1 sessions from 26.2 μs to 25.5 μs, and from 25.4 μs to 24.4 μs for the INT2 sessions.

We also tested estimating gradients with a priori gradients from ERA-Interim. As in Sec. 3.4, we varied the uncertainty of the a priori gradients, σ_{Grad}, from 0 mm to 1.5 mm. The results for UT1-UTC and LOD are also depicted in Fig. 3 and Fig. 4, respectively. We can see that the WRMS differences get smaller compared to when using the simple APG model for the a priori gradients. The σ_{Grad} values which give the smallest WRMS differences are 0.5 mm for the INT1 sessions and

0.7 mm for the INT2 sessions, i.e., 0.1 mm smaller than what was found in Sec. 3.4. This is likely because ERA-Interim gradients are closer to the real gradients than the APG model (which gives just a constant value per site and contains no time variation), thus smaller adjustments are needed and hence tighter constraints can be applied. For large σ_{Grad} values the difference between using a priori gradients from APG or ERA-Interim diminishes, which is expected. When the gradients are loosely constrained it is not important what a priori values are used.

3.6 Gradients from GPS

Another possibility to get a priori gradients is to use those estimated from GPS. We used gradients estimated in the GPS analysis described in Sec. 2.1. When we fix the gradients to those obtained from GPS, the UT1-UTC WRMS difference relative to the estimates from the reference solution is 21.4 μs, compared to 21.6 μs for the standard solution, i.e. there is no significant reduction in the WRMS (these WRMS values are only calculated using the sessions for which high quality GPS results are available for both stations, see Sec. 3.3).

As with the case of a priori ZWD from GPS, we also made tests where we included the GPS gradients as additional observations in the data analysis of the Intensives. Also here, the uncertainties of the GPS gradients were assumed to be their formal errors multiplied by a factor, which was varied between the different solutions. For σ_{Grad} of the a priori gradients we used here a large value (5 mm) in order to have the gradients effectively only constrained by the GPS data. The WRMS difference between the LOD from the Intensive solutions and IGS can be seen in Fig. 5. We can see that the inclusion of GPS gradients makes the

WRMS smaller. The best results are obtained when a factor for the GPS formal errors of about 2.5–3 is used, giving WRMS LOD differences of 22.9 μs for INT1 and 18.3 μs for INT2. The same conclusions can be drawn when comparing the UT1-UTC estimates with the reference solution, where the WRMS difference is 20.2 μs for INT1 when a factor of 2.5 is applied. All the decreases in WRMS are statistically significant. One reason, why the optimal factor is larger than 1, could be that the formal errors of the GPS gradients are too optimistic, or that there are systematic errors in these gradients. Furthermore, normally the GPS gradients are included at two epochs: the beginning and the end of the Intensive session. In the analysis, the GPS gradients are all assumed to be uncorrelated, however, this is not generally true. Hence, this could also be a reason why the formal errors need to be increased.

It is possible that there are unknown errors in the GPS estimated LOD, and when these values are fixed in the PPP processing will probably result in errors in the GPS gradient estimates. Thus, it could happen, that when these GPS gradients are used in the analysis of the Intensives, corresponding errors in the UT1-UTC estimates are introduced. Therefore, while the LOD agreement between the Intensives and GPS improves, the UT1-UTC estimates are actually degraded. An indication that this partly being the case is that the agreement between the UT1-UTC estimates of the Intensives and the 24-h VLBI sessions are not improving as much as the LOD agreement. When GPS gradients are included as additional observations and their formal errors are multiplied by a factor of 3, the agreement for UT1-UTC and LOD from the INT1 sessions improves by 6.5 % and 12 % respectively. Hence, as an additional independent test, we also compared the LOD from the INT1 Intensives to the LOD estimated from the 24-h sessions. Here we found that the WRMS LOD difference decreased from 29.1 μs to 27.2 μs, i.e., by 6.5 %, which is smaller than the decrease in the WRMS difference we obtain when comparing with IGS LOD. Partly this is because that the LOD from VLBI has slightly larger uncertainty than the IGS LOD (indicated by the higher WRMS values), however, it cannot be excluded that partly it is because of the correlated errors in GPS gradient and LOD estimates.

4 Conclusions

The results show that the UT1-UTC estimates are significantly impacted by the troposphere, in particular the tropospheric gradients. Thus, we can improve the results by using a more sophisticated modeling of the tropospheric parameters in the data analysis. This can include better a priori information, including observations of the tropospheric parameters from other techniques, or to estimate additional tropospheric parameters like gradients.

Including additional information on the ZWD, e.g., from GPS, typically makes the agreement with the reference time series worse. If only the GPS ZWD are included with a small weight in the INT1 sessions, a marginal reduction in the WRMS differences (1 %) is found. The reason is that the ZWD can be well determined in the data analysis of modern-day Intensives, thus additional information is not needed. Using external ZWD from GPS or NWM could, however, be interesting for re-analysis of older Intensive sessions from the 80s and early 90s, although it should be noted that reliable GPS data are only available from the mid 90s. Since the older Intensives did not have as many observations as modern-day Intensives, it is sometimes not possible to estimate the ZWD. Hence, for these sessions external ZWD will be beneficial.

We recommended that a priori tropospheric gradients calculated from a NWM are used since this improves the agreement with the reference series compared to when applying simple empirical models such as APG. In fact, there is almost no benefit in using an empirical gradient model compared to no gradient model at all (i.e., zero a priori gradients). We have made investigations where zero a priori gradients were used and found very small differences compared to when APG was applied. Thus, it is important to model the temporal variations in the gradients, not only the climatological mean.

Tropospheric gradients are typically not estimated in the data analysis of Intensive sessions, however, as demonstrated by our results this is possible when appropriate constraints are applied. When estimating gradients the UT1-UTC and LOD estimates are closer to the reference series, in particular for the INT2 sessions. Thus, we recommend that gradients should also be estimated when analyzing Intensive sessions, in particular the INT2 sessions.

We obtain a reduction in the WRMS differences to the reference series when including external gradients from GPS in our analysis, confirming the results of Teke et al. (2015). When estimating gradients and including the GPS gradients as additional observations in the data analysis, the reduction of the WRMS differences is significant. In principle, further improvements could be expected if we additionally use a priori gradients from ERA-Interim. However, in our tests we found no significant further changes.

In the future, we will also test using a priori tropospheric delays obtained from ray-tracing through NWMs. The results of, for instance, Böhm et al. (2010) and

Nafisi et al. (2012) indicate that this can improve the results from the Intensives. The advantage of using ray-tracing, especially if a high resolution NWM is used, is that also non-linear horizontal variations will be modeled, not only the linear ones described by the gradients. Furthermore, we will study other potential error sources, such as the a priori EOP and unmodeled nonlinear station motions.

Acknowledgements We are grateful to the IVS for providing the data from the Intensive sessions (Nothnagel et al., 2015), the IGS for providing the GPS data and the LOD series, and Jan Douša for providing the gradients. We are also grateful to the three anonymous reviewers for their comments which helped us improving the paper.

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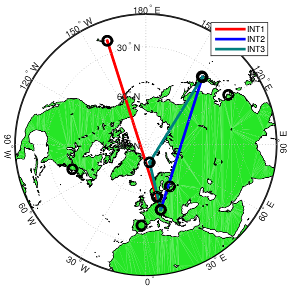

Fig. 1 Map of the stations which participated in the Intensive sessions from 2002–2015. The stations nominally participating in a particular type of Intensive sessions are connected by lines. The other stations marked with black circles are those which have participated occasionally.

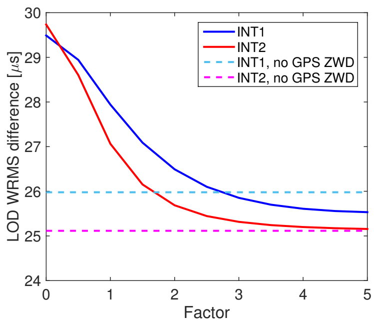

Fig. 2 WRMS difference between the LOD from the Intensives and IGS, when using ZWD from GPS as additional observations in the Kalman filter. The uncertainties of the GPS ZWDs are assumed to be their formal errors multiplied with a constant factor. Shown are the WRMS values as a function of this factor. The dashed lines show the results when no GPS ZWDs are included in the solution.

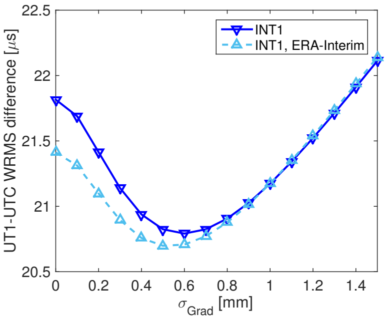

Fig. 3 WRMS differences between the UT1-UTC from the Intensives and those from the reference solution, when gradients are estimated in the data analysis. Shown are the WRMS values as a function of the assumed uncertainty of the a priori gradients, σ_{Grad}. The results from two solutions are shown, the standard one with a priori gradients from the empirical APG model (Böhm et al., 2013) and a solution with a priori gradients calculated from ERA-Interim data.

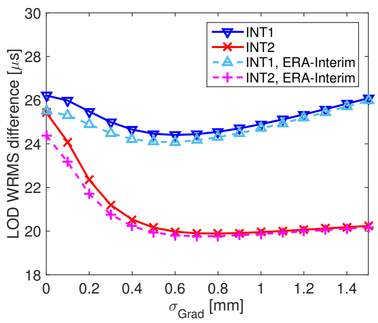

Fig. 4 Same as Fig. 3, except that here the WRMS differences between the LOD values estimated from the Intensives and those from IGS are shown.

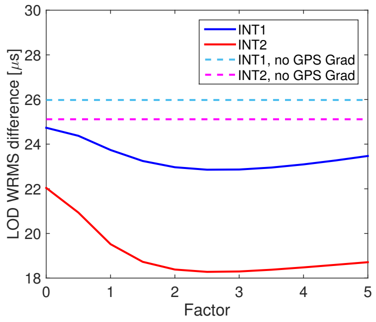

Fig. 5 WRMS difference between the LOD from the Intensives and IGS, when using gradients from GPS as additional observations in the Kalman filter. The uncertainties of the GPS gradients are assumed to be their formal errors multiplied by a constant factor. Shown are the WRMS values as function of this factor. The dashed lines show the results when no GPS gradients are included in the solution and gradients are not estimated.

Table 1 WM (WRMS) differences between the UT1-UTC estimated from the Intensive sessions and from the reference solution (simultaneous 24-h VLBI sessions). Shown are the results of one classical least-squares solution (LSM) and two Kalman filter solutions: one where all sessions are analyzed individually (KF sing), and another where loose constraints are used in between the sessions (KF cont).

Baselines	LSM [μs]	KF sing [μs]	KF cont [μs]
Wettzell–Kokee	0.4 (22.6)	0.4 (22.2)	0.5 (21.8)
Others	0.3 (21.4)	0.2 (20.8)	0.3 (20.4)
All	0.4 (22.5)	0.4 (22.0)	0.4 (21.7)