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GNSS zenith delays and gradients in the analysis of VLBI Intensive sessions

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Abstract

Very Long Baseline Interferometry (VLBI) is the only space geodetic technique which is capable of estimating Universal Time (UT1 = UTC + ΔUT1). So-called VLBI Intensive sessions of the International VLBI Service for Geodesy and Astrometry (IVS) are dedicated to the rapid production of ΔUT1. However, the accuracy achieved with those sessions is still below what could be expected from formal uncertainties of the estimates and one of the reasons is the inappropriate modeling of azimuthal asymmetries of the troposphere delays, because usually no gradients are modeled or estimated. To overcome that deficiency, we introduced troposphere zenith delays and horizontal total gradients estimated from the observations of Global Navigation Satellite Systems (GNSS) i.e. the solution of the Center for Orbit Determination in Europe (CODE) in the analysis of VLBI Intensive sessions carried out from the beginning of 2008 till the end of 2014. We compared our results with the GNSS-derived length-of-day (LOD) estimates of CODE and the International GNSS Service (IGS) and find slight improvements of agreement by up to 1 μs for both INT1 and INT2 sessions with gradients from CODE. We do not see any additional significant improvement of LOD agreement when GNSS zenith delays are introduced.

Keywords: VLBI; Intensive sessions; Universal Time 1; Length of day; Troposphere gradients from GNSS

1. Introduction

Troposphere delay modeling is a major error source in the analysis of space geodetic observations at radio frequencies, e.g. from the Global Navigation Satellite Systems (GNSS) and geodetic Very Long Baseline Interferometry (VLBI). Usually, the troposphere total delay of the observable is modeled as (Davis et al., 1993).

$$SD(\varepsilon,\alpha) = ZHD \cdot mf_h(\varepsilon) + ZWD \cdot mf_w(\varepsilon) + mf_g \cdot (G_n \cdot \cos\alpha + G_e \cdot \sin\alpha). \quad (1)$$

The total slant delay SD at an elevation angle ε and azimuth α is the sum of a hydrostatic delay and a wet delay, and each of them is the product of a zenith delay and the corresponding mapping function. While the zenith hydrostatic delay can be calculated very accurately with the pressure at the antenna and approximate station coordinates following the formula by Saastamoinen (1972) as revised by Davis et al. (1985), the zenith wet delays are usually estimated in the analysis of space geodetic observations as unknown parameters. Furthermore, north and east horizontal total gradients, G_n and G_e, are also estimated in

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the analysis to account for azimuthal asymmetries in the troposphere delays. The gradient mapping function mf_g times the cosine and the sine of the azimuth serves as partial derivative to determine the gradients in the least-squares adjustment. Usually, the formulation by Davis et al. (1993) as modified by MacMillan (1995) or the equation by Chen and Herring (1997) with $C = 0.0032$ as gradient mapping function are applied. For more information about troposphere delay modeling in space geodesy we refer to an overview paper by Nilsson et al. (2013).

In contrast to VLBI 24 h sessions with about six or more participating stations, gradients are usually not estimated in the analysis of Intensive sessions of the International VLBI Service for Geodesy and Astrometry (IVS; Schuh and Behrend, 2012) with just two or three stations observing for one or two hours with the sole purpose to determine Universal Time ΔUT1 (UT1–UTC). The so-called INT1 sessions (Intensives 1) are usually observed from Monday to Friday at about 18 UT on the baseline Wettzell (Germany) to Kokee (Hawaii, USA). Sometimes, also station Svetloe (Russia) joins the observations, and for several weeks, the baseline Wettzell to Kokee was replaced by the baseline Wettzell to Tsukuba (Japan) or Kokee to Ny-Ålesund (Spitsbergen, Norway). Additionally, the INT2 sessions (Intensives 2) are observed on the baseline Wettzell to Tsukuba at about 7 UT on Saturdays and Sundays and on Mondays INT3 sessions (Intensives 3) are observed including Ny-Ålesund (Luzum and Nothnagel, 2010) with frequent participation by Seshan (China). The baseline geometry of the INT1 and INT2 sessions is shown in Fig. 1. The projection of the baseline onto the equatorial plane needs to be long to sustain high sensitivity of the VLBI observations to ΔUT1 (Nothnagel and Schnell, 2008; Nilsson et al., 2011). However, long baselines of the IVS Intensive sessions limit the number of sources to be observed simultaneously by both antennas resulting in poor sky coverage. This is in contradiction to the fact that a homogeneous distribution of the observations in the sky is essential for a realistic zenith wet delay and gradient estimation at the corresponding station which is required for the accurate determination of ΔUT1 from Intensive sessions. Due to the fact that GNSS observations have a much better sky coverage compared to VLBI Intensive sessions we expect a significant accuracy improvement of ΔUT1 from Intensive sessions when GNSS troposphere delays are used for the analysis of Intensive sessions at co-location sites.

Several accuracy assessments on ΔUT1 observed by the Intensive sessions of the IVS were carried out in the past, e.g. by Robertson et al. (1985), Ray et al. (1995), Hefty and Gontier (1997). However, due to the small number of observations in the Intensive sessions at that time (1984–1996) zenith wet delays could not be estimated. Titov (2000) assessed the effect of nutation models, i.e. IAU 1980 (Wahr, 1981) and IERS 1996 (Herring, 1996), on ΔUT1 estimates. Baver et al. (2004) analyzed IVS INT1 and INT2 sessions observed from July 2002 till December 2003, compared their UT1 estimates with those of 24 h IVS sessions and IERS C04, and investigated the effects of the observed sources distribution on UT1 formal errors for Intensive sessions. More recently, Nothnagel and Schnell (2008) investigated the propagation of the errors in polar motion and nutation angles on ΔUT1 estimates in the analyses of Intensive sessions. Thaller et al. (2008) found an accuracy improvement of ΔUT1 from Intensive sessions, observed from November 2006 until February 2008, when a combination with GPS solutions at the normal equation level is performed.

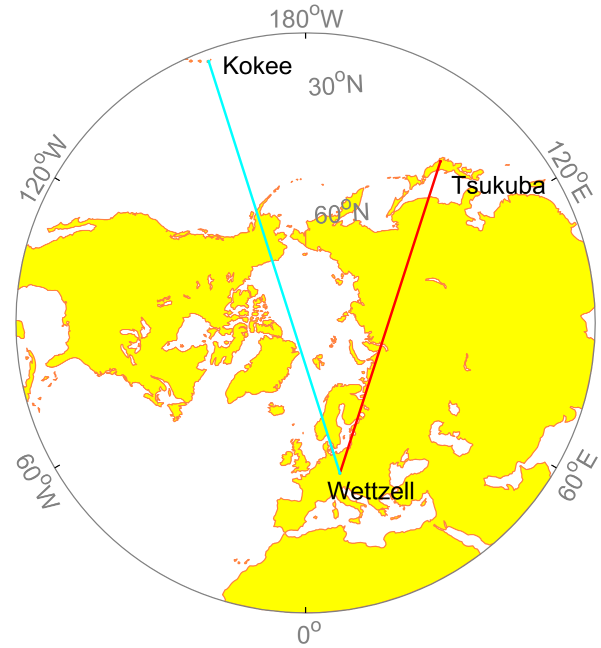

Fig. 1. Baseline geometry of the VLBI Intensive sessions, INT1 and INT2. The INT1 baseline is plotted in cyan and the INT2 baseline in red (stereographic map projection). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

While in multi-station networks the average over all troposphere gradients tends to be zero and the impact on estimated Earth orientation parameters is rather small, ΔUT1 from single baselines can be significantly wrong. Böhm and Schuh (2007a) found a systematic change of ΔUT1 by 15 μs/mm sum of east gradients; on the other hand they stated that the estimation of zenith wet delays is not critical for the accuracy of ΔUT1 since troposphere mapping function errors mainly affect station heights rather than horizontal components and the influence of mapping function errors on ΔUT1 is rather small, i.e. below ±1.5 μs. Consequently, they concluded that an improved modeling of azimuthal asymmetries in the troposphere delays is highly desirable for accurate ΔUT1 estimation from the observations of Intensive sessions.

Böhm and Schuh (2007b) derived gradients from refractivity profiles along the site verticals and found improved accuracies compared to zero gradients in the analysis of

24 h VLBI sessions. Böhm et al. (2010) and Nafisi et al. (2012) applied ray-traced delays in the analysis of Intensive 2 sessions and found a slight improvement when comparing length-of-day values from adjacent Intensive sessions to those derived from GNSS. Nilsson et al. (2011) demonstrated that the accuracy of Intensive sessions can be improved when using external information about the gradients or when estimating gradients using 2 h single baseline sessions during the IVS-CONT08 campaign. Nilsson et al. (2014) found weighted root mean square differences between VLBI and GNSS length-of-day (LOD) estimates from 2010 until 2012 with values of 16.4 μs for IVS-R1 sessions and 21.4 μs for IVS-R4 sessions. On the other hand, they found smaller weighted root mean square differences between GNSS LOD and VLBI estimates from CONT08 and CONT11 campaigns with values of 8.0 μs and 6.8 μs, respectively. The better agreement of LOD between VLBI CONT campaigns and GNSS found by Nilsson et al. (2014) is due to the different characteristics of the IVS session types, i.e. CONT sessions versus Intensive sessions, with CONT sessions including more antennas and radio sources and having a better temporal and spatial distribution of observations. In addition to the troposphere gradients, corrections to the a priori polar motion coordinates and celestial pole offsets can be estimated in the analyses of CONT sessions which at the end results in a better accuracy of LOD from CONT sessions compared to Intensive sessions.

In this study, we used GNSS zenith delays and gradients as derived from the solution of the Center for Orbit Determination in Europe (CODE, Dach et al., 2009) in the analysis of VLBI Intensive sessions, i.e. INT1 and INT2 observed from the beginning of 2008 till the end of 2014. We selected certain Intensive sessions according to the availability of zenith delays and gradients estimated by CODE analyses at co-located GNSS sites. Co-located GNSS and VLBI sites have the same atmosphere conditions at the same observation epochs provided the horizontal distance between the co-located sites is not too long (maximum in this study at Tsukuba with about 300 m, see Table 1) and the troposphere zenith delays are corrected due to the height differences between the co-located antennas (Saastamoinen, 1972; Brunner and Rüeger, 1992; Teke et al., 2013).

Zenith delay corrections due to the atmosphere between co-located GNSS and VLBI antennas were introduced to the zenith delay estimates of GNSS relative to a reference height at the co-location sites. We selected the height of the VLBI antenna reference point as the reference height of the corresponding co-located site. We used the mean values of the zenith delay corrections of a series of continuous IVS campaigns (CONT02, CONT05, CONT08, and CONT11) as reported by Teke et al. (2013) (Table 1, last column) in one of our solutions of Intensive sessions in this study. They introduced zenith delay corrections at co-location sites and quantified the agreement of the zenith delay and gradients derived from various space geodetic techniques and numerical weather models where they calculated zenith hydrostatic delay corrections according to Saastamoinen (1972, 1973) and wet corrections according to Brunner and Rüeger (1992) using total pressure, water vapor pressure, and temperature values at co-location sites derived from re-analysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011).

UT1 estimates of Intensive sessions must be available soon after the session observed so as to be useful for UT1 prediction e.g. for near real-time applications. According to Schuh and Behrend (2012), IVS Intensive sessions i.e. INT1 and INT2 have a latency of one or two days, means that the observation file of an Intensive session is ready for the analysis one or two days after the session observed. On the other hand, CODE ultra-rapid solution has a maximum delay of 3 h after the observation with the troposphere product delivery at 3:00, 9:00, 15:00, and 21:00 UT. This means that the latencies of the INT1 and INT2 sessions are much larger than the latency of GNSS troposphere delays. Thus, there is not any additional latency of UT1 due to the availability of the GNSS troposphere delays. However, ultra-rapid UT1 experiments using electronic data transfer (eVLBI), e.g. Matsuzaka et al. (2008), Sekido et al. (2008), Haas et al. (2010) and Weimin et al. (2012), would need near real-time GNSS troposphere delays.

In Section 2, we introduce the parameterization of certain types of solutions of VLBI Intensive sessions observed from the beginning of 2008 till the end of 2014 and the properties of the GNSS zenith delays and gradients

Table 1
ITRF2008 ellipsoidal heights and approximate horizontal distances between co-located VLBI and GNSS antennas which contributed to IVS INT1 and INT2 sessions from the beginning of 2008 till the end of 2014 and are considered in this study along with the mean zenith delay corrections due to height differences between GNSS and VLBI antennas. Co-location sites are ordered according to their latitude from north to south.

Co-location sites	Latitude (°)	Country	VLBI acronym	Height VLBI site (m)	GNSS site acronym	VLBI–GNSS approximate horizontal distance (m)	Height GNSS site (m)	VLBI–GNSS height difference (m)	VLBI–GNSS mean zenith delay corrections (mm)
Wettzell (wtzr)	49.1	Germany	Wettzell	669.1	wtzr	139	666.1	3.0	−0.9
Tsukuba (tskb)	36.1	Japan	Tsukub32	84.7	tskb	302	67.3	17.4	−6.1
Kokee park (kokb)	22.1	USA	Kokee	1176.6	kokb	45	1167.4	9.2	−2.7

estimated at co-location sites from CODE solution that we reduced from VLBI observations of Intensive sessions a priori to the parameter estimation. In Sections 3.1 and 3.2, we discuss the impact of externally introduced zenith delays and gradients from the GNSS analyses, i.e. from CODE, on the ΔUT1 estimates of VLBI Intensive sessions. In Section 3.3, we compare ΔUT1 and LOD estimates of our solutions of VLBI Intensive sessions with respect to the IERS C04 08 series and the LOD estimates of the CODE and IGS solutions, respectively. The conclusions are presented in Section 4.

2. Analysis of VLBI Intensive sessions

We only consider the baseline Wettzell–Kokee for INT1 sessions and Wettzell–Tsukuba for INT2 sessions in this study. Among the 1575 INT1 sessions planned by the IVS from the beginning of 2008 till the end of 2014, we included only the observations of Wettzell and Kokee antennas in our analyses. During this time span of about seven years, there were 121 INT1 sessions observed with Svetloe and 23 INT1 sessions with Nyales20. Instead of removing the whole INT1 sessions from the analyses in which Svetloe and Nyales20 took part we excluded the observations of these antennas from the analyses. The IVS planned to observe in total 577 INT2 sessions from the beginning of 2008 till the end of 2014 with only the antennas Wettzell and Tsukub32. On the other hand, 206 INT3 sessions with the observations of Nyales20 and 22 INT3 sessions with the observations of both Nyales20 and Seshan25 are not considered in this study. Moreover, we exclude certain INT1 and INT2 sessions from the analyses due to the following reasons: large a posteriori variance of unit weight compared to the a priori variance, large formal error of UT1 estimate (larger than 30 μs), unavailability of the GNSS CODE delays around the observations of Intensive sessions (-2.5 h < middle of the Intensive session < 2.5 h), large zenith delay and gradient errors estimated from the GNSS CODE solution (GNSS CODE zenith delays and gradients are important since we externally introduce them into Intensive sessions). After eliminating these Intensive sessions the remaining 1434 INT1 and 451 INT2 sessions with available GNSS CODE delays were included in our analyses. The average number of observations per session is about 20 for INT1 and 38 for INT2 sessions.

We carried out four types of VLBI solutions to quantify the effect of GNSS troposphere delays on ΔUT1 and LOD estimates of Intensive sessions. For all solutions, we calculated the zenith hydrostatic delay (ZHD_{VLBI}) with total surface pressure values measured at the VLBI sites (Saastamoinen, 1972; Davis et al., 1985) and mapped them with the hydrostatic Vienna Mapping Functions 1 (VMF1, Böhm et al. 2006) to get the slant hydrostatic delays. We subtracted the slant hydrostatic delays from each VLBI observation of the Intensive sessions a priori to the parameter estimation. Differences between our solutions are just in terms of zenith delay and gradient parameterizations.

- *Standard solution (Solution 1):* We analyzed the Intensive sessions with a standard Intensive session analysis procedure. In this procedure, one zenith wet delay offset for each VLBI site per session is estimated and gradients are fixed to zero.
- *Solution with gradients from GNSS (Solution 2):* One zenith wet delay offset for each VLBI site per session is estimated as also done in the *Standard solution* (*Solution 1*). The difference of this solution from *Solution 1* is that GNSS gradients are included in the analysis of Intensive sessions. In this approach we interpolated total gradients estimated from GNSS solution by CODE to the VLBI observation epochs linearly. We calculated azimuthally asymmetric troposphere delays through mapping the interpolated horizontal total north and east gradients to slant direction using the third term of Eq. (1) where the gradient mapping function by Chen and Herring (1997) was used.
- *Solution with zenith wet delays and gradients from GNSS (Solution 3):* In this solution, zenith wet delays and gradients from the GNSS solution by CODE were included in the analysis of Intensive sessions. Thus, we first interpolated zenith delay and gradient estimates of GNSS to the VLBI observation epochs linearly. Then, we added a mean zenith delay correction (ΔZTD) due to the height differences (Table 1, last column) to ZHD_{VLBI} of each co-located site. The GNSS zenith wet delays at the VLBI height, ZWD_{GNSS}@VLBI for each observation epoch were derived as $ZTD_{GNSS} - (ZHD_{VLBI} + \Delta ZTD)$. Thereafter, ZHD_{VLBI} and ZWD_{GNSS}@VLBI were mapped to slant elevations using VMF1. The azimuthally asymmetric delays were calculated in the same way as in *Solution 2*. Then, we reduced the total slant delays (sum of azimuthally symmetric and asymmetric delays) from each VLBI observation of the Intensive session a priori to the parameter estimation.

  The zenith delay differences due to the atmosphere between co-located antennas might slightly change with respect to the mean values (given in the last column of Table 1) from one Intensive session to another. Thus, we estimated one zenith wet delay offset (which has a very small value in the order of a few millimeters at maximum) for each session to eliminate the residual zenith delays from the observations.

- *Solution with zenith wet delays and gradients from GNSS without height corrections (Solution 4):* We keep the same parameterization as in *Solution 3* except that neither mean zenith delay corrections are introduced nor zenith wet delays are estimated.

All the other parameterization of these four types of solutions is as follows: We analyzed VLBI Intensives using the Vienna VLBI Software (VieVS, Böhm et al., 2012) Version 2.2, which is developed at the Department of Geodesy and Geoinformation at the Vienna University of Technology. The classical Gauss-Markoff least-squares adjustment method was used for estimating the parameters. We did not exclude any observation below a certain cut off elevation angle nor did we apply elevation dependent down-weighting to the observations. We fixed source coordinates to ICRF2 (International Celestial Reference Frame 2, Fey et al., 2009), nutation offsets to IAU2000A nutation model plus IERS C04 08 corrections (Bizouard and Gambis, 2009) and polar motion coordinates to IERS C04 08 plus high-frequency tidal terms modeled as recommended by the IERS Conventions 2010 (Petit and Luzum, 2010). One constant ΔUT1 offset for each Intensive session was estimated with respect to IERS C04 08. We fixed antenna coordinates to the VieTRF13b catalogue (Krásná et al., 2014). Tidal and non-tidal atmospheric loading corrections (Petrov and Boy, 2004), tidal ocean loading corrections based on the ocean model FES2004 (Lyard et al., 2006), pole tide and ocean pole tide corrections (Petit and Luzum, 2010) were introduced to the antenna coordinates for each observation a priori to the parameter estimation. One offset and a rate between the clocks were estimated.

The CODE zenith delays and gradients used in this study were computed with the Bernese GNSS Software version 5.3 (Dach et al., 2007). They are obtained from the CODE contribution to the 2nd IGS reprocessing campaign (repro2). The general processing strategy is discussed in Steigenberger et al. (2006) and Steigenberger et al. (2011). Full information about the models and processing strategies used for the CODE contribution to repro2 is given in the CODE Analysis Strategy Summary for IGS repro2.[1] Troposphere zenith delays and gradients were estimated in a global GPS/GLONASS double difference solution together with station coordinates, GNSS satellite orbits, and Earth rotation parameters. CODE provided two different solutions for IGS repro2: a pure 1-day solution (co2) and a 3-day solution (cf2). The results presented in this paper are based on the 1-day solution.

Hydrostatic a priori zenith delays were obtained from 6-hourly global grids from ECMWF. A linear interpolation regarding time, latitude, and longitude was applied and the resulting zenith hydrostatic delay was extrapolated from the grid height to the actual station height according to Kouba (2008). Troposphere zenith wet delays and gradients were estimated as a piece-wise linear function with 2 and 24 h parameter spacing, respectively. The wet VMF1 was used for the estimated zenith wet delays and the mapping function of Chen and Herring (1997) for the gradients. Elevation-dependent weighting with $\sin^2\varepsilon$ and a 3° cut off angle were applied.

[1] ftp://ftp.unibe.ch/aiub/REPRO_2013/CODE_REPRO_2013.ACN

LOD from the CODE solution was estimated in the CODE repro2 contribution as one LOD parameter per day. Due to correlations with the orbital elements, satellite techniques like GNSS are not able to determine ΔUT1 (Rothacher et al., 1999). However, the first derivative of ΔUT1, namely LOD, can be estimated from GNSS observations. Therefore, the first ΔUT1 value at 0:00 UT was fixed to IERS C04 08 and the second value at 24:00 UT was estimated as piece-wise linear function, i.e., only LOD was estimated. Diurnal and semidiurnal variations in ΔUT1 as well as the ΔUT1 libration were considered according to Petit and Luzum (2010).

The LOD product of IGS (Dow et al., 2009), used for the statistical comparisons of this study, are estimated at daily epochs (12 UT) from the combined solutions of IGS analyses centers (AC). The IGS LOD formal uncertainties from the combination are about 5 μs. In terms of external comparisons, the standard deviation of the combined IGS LOD with respect to the IERS Bulletin A for GPS weeks 1400–1476 is calculated as ±10 μs, as concluded by Ferland and Piraszewski (2009).

3. Results

In this section, we investigated the effect of externally introduced GNSS (CODE) zenith wet delays and gradients on the ΔUT1 estimates of Intensive sessions. Then, we present the comparison results of LOD estimates between our solutions of Intensive sessions and those of IERS C04 08 and the LOD from the CODE and IGS solutions.

3.1. The effect of GNSS zenith wet delays on ΔUT1 estimates of Intensive sessions

The standard deviations of zenith wet delay differences between GNSS CODE and *Solution 1* of VLBI Intensive sessions are 7.5 mm and 7.6 mm at Wettzell and Kokee for INT1 and 4.2 mm and 7.4 mm at Wettzell and Tsukuba for INT2 from the beginning of 2008 till the end of 2014 (Fig. 2). Due to the large seasonal variations and rapidly changing humidity at Tsukuba where the mean zenith wet delay is about 137 mm and the standard deviation 105 mm, the mean bias and standard deviation of the zenith wet delay differences between *Solution 1* of VLBI INT2 and GNSS CODE is -1.0 ± 7.4 mm. We recommend the reader to see the zenith wet delay time series of GNSS CODE and *Solution 1* of VLBI INT2 at Tsukuba provided in the Supplementary material of this paper. While the zenith wet delay mean biases are rather similar for INT1 and INT2 at Wettzell there is a large difference of standard deviations of about 3.3 mm (7.5 mm – 4.2 mm) (Fig. 2).

In contrast to Tsukuba and Wettzell a seasonal variation cannot be seen at Kokee in the zenith wet delay time series. The zenith wet delays at Wettzell and Kokee extend up to approximately 200 mm whereas at Tsukuba they reach up to about 400 mm. Zenith wet delay differences at VLBI observation epochs of Intensive sessions between

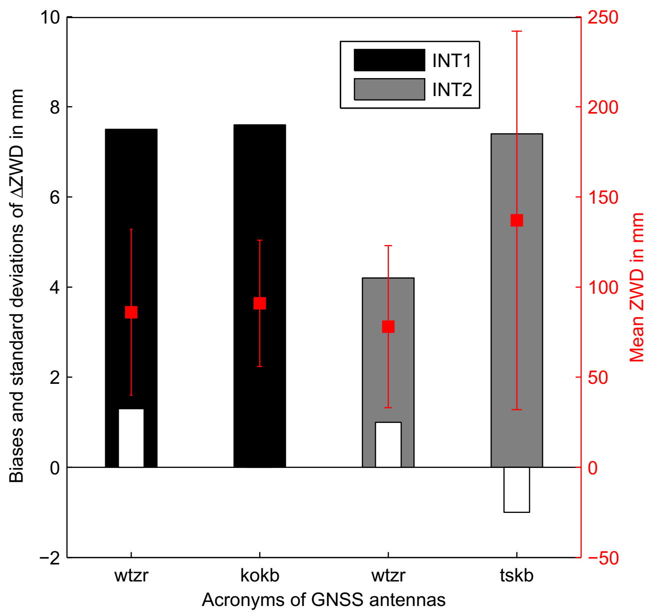

Fig. 2. Biases (white bars) and standard deviations (black and gray bars) of the zenith wet delay (ZWD) differences (ΔZWD) between GNSS CODE and VLBI by site from the beginning of 2008 till the end of 2014. Mean zenith wet delays and their standard deviations are shown in red. The zenith wet delays from VLBI were estimated by *Solution 1*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

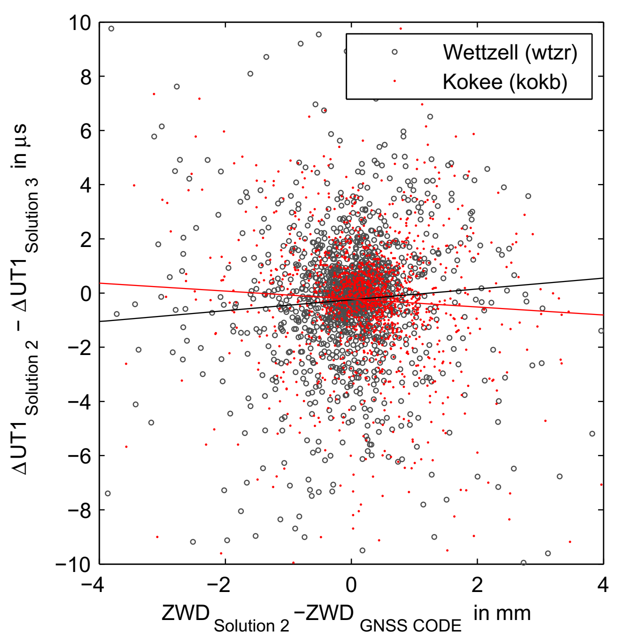

Fig. 3. Station wise zenith wet delay differences per INT1 session between the estimates of *Solution 2* and GNSS CODE versus ΔUT1 differences between *Solution 2* (Solution with zenith wet delays estimated, gradients from GNSS CODE) and *Solution 3* (Solution with both zenith wet delays and gradients from GNSS CODE). The lines are linear polynomial fits to the scattered data.

GNSS CODE and VLBI INT1 can be as large as ±20 mm at all co-located sites of this study (see Supplementary material).

The zenith wet delay differences between the estimates of *Solution 2* (*Solution with gradients from GNSS, i.e. CODE*) and GNSS CODE at Kokee (kokb) and Wettzell (wtzr) co-location sites mostly vary within ±4 mm while ΔUT1 differences between *Solution 2* and *Solution 3* vary within ±10 µs (Fig. 3). The linear correlation between zenith wet delay and ΔUT1 differences is found to be nearly negligible. On the other hand, zenith wet delays are highly correlated with other parameters like clock estimates; thus, we find that the variation of ΔUT1 estimates with zenith wet delay changes can increase up to a 20 µs level (Fig. 3).

3.2. The effect of GNSS gradients on ΔUT1 estimates of Intensive sessions

The standard deviations of GNSS CODE east and north gradients are largest at Tsukuba (tskb) with the values of 0.5 and 0.6 mm, respectively. The mean biases of gradients from GNSS CODE range from −0.5 to 0 mm for all sites during INT1 and INT2 sessions. We found standard deviations and mean biases of east gradients for INT2 slightly smaller than those of north gradients for both wtzr and tskb sites (Table 2).

East troposphere gradients at the observing stations reveal a clear linear impact on ΔUT1 estimates of Intensive sessions as shown in the left plot of Fig. 4. When GNSS CODE gradients are introduced a priori to the VLBI observations of Intensive sessions (*Solution 2*) the effect of the sum of east gradients over the stations on ΔUT1 estimates of INT1 sessions (Wettzell–Kokee) is 12.9 µs/mm (inferred from the rate of the linear fit to the black plus signs scattered in the left plot of Fig. 4) and for the INT2 sessions (Wettzell–Tsukuba) it is 10.7 µs/mm. Böhm and Schuh (2007a) and Nilsson et al. (2011) found similar results of ΔUT1 change by 15 µs/mm and 10–12 µs/mm sum of east gradients after their analyses of VLBI Intensive sessions, respectively. As expected, we could not find a significant linear impact of the sum of north gradients over the stations on ΔUT1 estimates when CODE gradients are a priori introduced in the analyses of both INT1 and INT2 sessions carried out from the beginning of 2008 till the end of 2014 (right plot of Fig. 4, see also the Supplementary material for INT2).

3.3. ΔUT1 and length-of-day (LOD) comparisons

When we compared ΔUT1 estimates from our solutions of Intensive sessions with those of IERS C04 08 a slight improvement of ΔUT1 agreement in biases and standard deviations is found for the INT1 Intensive sessions when GNSS gradients from CODE solutions were introduced and zenith wet delays are estimated (*Solution 2*) compared to the standard solution (*Solution 1*) (Table 3). However, since ΔUT1 estimates from Intensive sessions are mainly used for the production of IERS C04 08 series, comparisons of estimated ΔUT1 with IERS C04 08 series may

Table 2
Mean biases and standard deviations of north and east gradients (G_n and G_e) estimated from GNSS CODE solution in mm.

GNSS sites	Biases and standard deviations			
	INT1 sessions		INT2 sessions	
	G_n from $GNSS_{CODE}$	G_e from $GNSS_{CODE}$	G_n from $GNSS_{CODE}$	G_e from $GNSS_{CODE}$
wtzr	-0.2 ± 0.4	0.0 ± 0.4	-0.2 ± 0.4	0.0 ± 0.3
tskb	–	–	-0.4 ± 0.6	0.0 ± 0.5
kokb	-0.5 ± 0.5	-0.2 ± 0.5	–	–

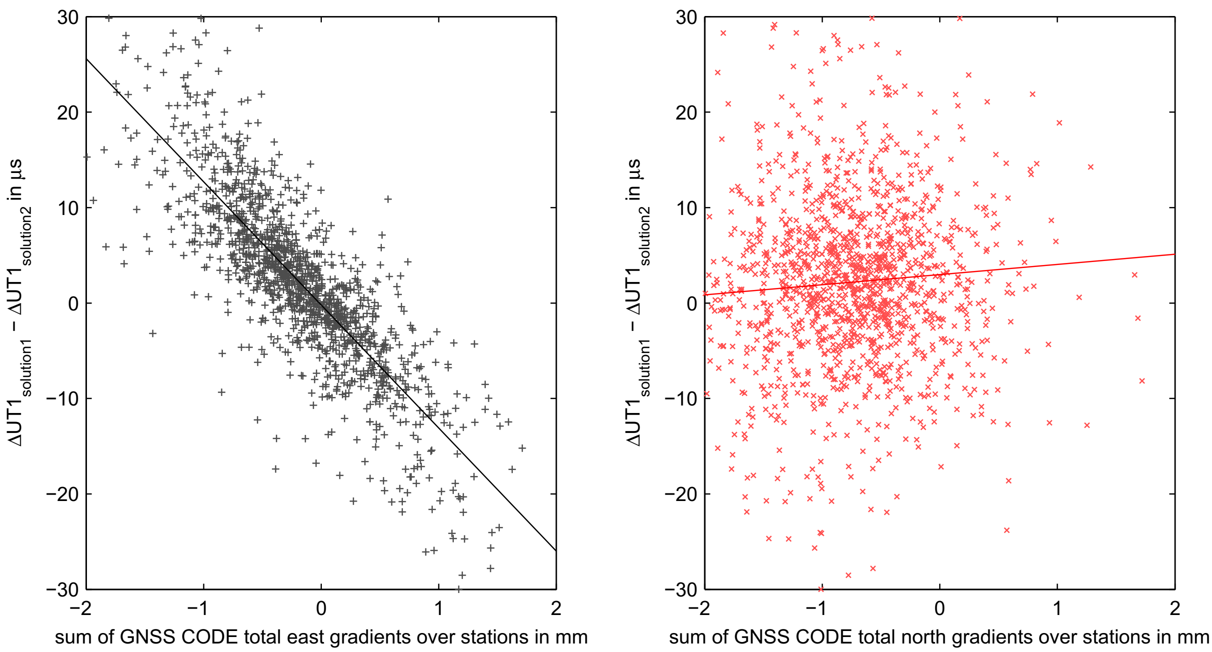

Fig. 4. Sum of total east (black plus signs) and north gradients (red crosses) from CODE over the observed stations which are included in *Solution 2* versus ΔUT1 differences between *Solution 1* (Standard solution: gradients fixed to zero) and *Solution 2* (Solution with gradients from GNSS CODE) for INT1 sessions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Biases and standard deviations of ΔUT1 differences in μs between IERS C04 08 series, hourly estimates from a global solution of CONT14, and those estimated from the solutions of VLBI Intensive sessions, i.e. INT1 and INT2, observed from the beginning of 2008 till the end of 2014. The a priori EOP series was set to IERS C04 08 when analyzing the sessions. The total number of ΔUT1 values used for the bias and standard deviation calculations is given in parentheses. ΔUT1 median formal errors of all Intensive solutions are written in μs in brackets.

Solution Type	INT1 – IERS C04 08 (1434 ΔUT1 values)	INT2 – IERS C04 08 (451 ΔUT1 values)	INT1 – CONT14 (10 ΔUT1 values)
Solution 1	5.0 ± 18.4 [11.4]	2.1 ± 20.3 [7.5]	9.0 ± 12.1
Solution 2	2.9 ± 18.3 [11.3]	1.2 ± 22.2 [7.5]	6.2 ± 7.7
Solution 3	3.1 ± 18.3 [11.3]	1.4 ± 22.4 [7.5]	6.3 ± 7.6
Solution 4	2.8 ± 21.0 [10.9]	2.7 ± 26.2 [8.2]	7.2 ± 9.4

not be the best way of assessing ΔUT1 accuracy improvement.

Every third year IVS schedules and observes continuous VLBI (CONT) campaigns over two weeks to demonstrate the highest accuracy reached by the current VLBI system (Schuh and Behrend, 2012). In order to see the results of ΔUT1 comparisons from the optimal parameterization and observation conditions we compared ΔUT1 from INT1 solutions with the hourly piece-wise-linear ΔUT1 estimated from a global solution of the last IVS CONT campaign, CONT14, observed from 6 to 20 May 2014. The standard deviations of ΔUT1 differences between INT1 and CONT14 sessions decrease significantly from 12.1 to 7.7 μs when daily gradients from GNSS CODE are introduced in the analysis of INT1 sessions (Table 3).

A better assessment of the accuracy improvement of ΔUT1 with GNSS slant delays is realized by comparing LOD estimates from Intensives with LOD from GNSS. In general, LOD estimates from GNSS are independent of VLBI. However, when computing the combined IGS LOD series, AC-specific 10-day bias corrections with respect to IERS Bulletin A are estimated. As VLBI

Table 4
Biases and standard deviations of LOD differences in μs between the estimates of VLBI Intensive sessions (INT1 and INT2) and those derived from the solutions of CODE, IGS and IERS C04 08. The total number of LOD used for the standard deviation calculations is given in parentheses.

Solution Type	INT1 – CODE (933)	INT1 – IGS (933)	INT1 – C04 08 (933)	INT2 – CODE (203)	INT2 – IGS (203)	INT2 – C04 08 (203)
Solution 1	14.0 ± 30.7	2.1 ± 29.3	3.4 ± 29.5	11.5 ± 22.8	−0.6 ± 22.1	0.0 ± 22.2
Solution 2	14.0 ± 29.9	2.1 ± 28.5	3.4 ± 28.5	11.2 ± 21.9	−0.9 ± 21.3	−0.3 ± 21.5
Solution 3	13.9 ± 29.7	1.9 ± 28.3	3.2 ± 28.4	11.4 ± 22.2	−0.7 ± 21.6	−0.1 ± 21.8
Solution 4	13.9 ± 31.9	2.0 ± 30.7	3.3 ± 30.8	9.9 ± 24.1	−2.3 ± 23.2	−1.6 ± 23.6

24-hour and Intensive sessions contribute to IERS Bulletin A, IGS LOD cannot be considered independent from VLBI anymore. We compared LOD estimated from our solutions of VLBI Intensives with those from CODE and IGS solutions in terms of calculating standard deviations of the LOD differences. We calculated LOD from the estimated ΔUT1 values of INT1 and INT2 sessions with

$$\mathrm{LOD}(t_0) = \left(\frac{\Delta\mathrm{UT1}(t_2) - \Delta\mathrm{UT1}(t_1)}{t_2 - t_1}\right) \cdot 1\,\mathrm{day} \qquad (t_2 - t_1 < 1.2\,\mathrm{day}) \tag{2}$$

where t_1 and t_2 are the consecutive estimation epochs of ΔUT1 and t_0 denotes the epoch of LOD and is calculated as $(t_1 + t_2)/2$. The daily LOD values from CODE and IGS solutions and IERS C04 08 series were interpolated to the LOD epochs of INT1 and INT2 VLBI Intensive sessions using Lagrange interpolation.

We found a slight improvement of LOD agreement in standard deviation of LOD differences between *Solution 2* (*Solution with gradients from GNSS*) and GNSS CODE and IGS solutions compared to *Solution 1* (*Standard solution*) by up to 1 μs when CODE troposphere gradients are introduced (Table 4).

As we expected, the agreement of LOD from *Solution 4* (*Solution with zenith wet delays and gradients from GNSS without height corrections*) with those of CODE, IGS and IERS C04 08 got worse compared to *Solution 1, Solution 2,* and *Solution 3* for both INT1 and INT2 sessions (Table 4).

When overall biases and standard deviations of LOD differences between the Intensive sessions and GNSS Solutions are considered, INT2 sessions reveal a better agreement than INT1 with GNSS solutions (CODE and IGS) and IERS C04 08. The mean biases and standard deviations of the LOD differences between CODE – IGS, CODE – IERS C04 08, and IGS – IERS C04 08 are found as -12.6 ± 13.3, -10.7 ± 12.3, and 1.3 ± 6.2 μs, respectively. The small bias of the IGS LOD with respect to IERS C04 08 is related to bias corrections mentioned above whereas no such correction is applied for CODE. We get the best agreement of LOD, in standard deviation of LOD differences, between *Solution 2* (when zenith wet delays are estimated and gradients are introduced from GNSS CODE in the analysis) of INT2 sessions and GNSS IGS with a standard deviation of 21.3 μs. The second best agreement of LOD, in standard deviation of LOD differences, is found between *Solution 2* of INT2 sessions and IERS C04 08 series with a standard deviation of 21.5 μs. Considering INT1 sessions, the smallest standard deviation of the LOD differences is found between *Solution 3* and IGS with the value of 28.3 μs. When GNSS CODE zenith wet delays are introduced in *Solution 3* to the observations of INT2 sessions, LOD agreement gets slightly worse relative to *Solution 2* even though the agreement is better than for *Solution 1*. Compared to *Solution 1* (*Standard solution*) we obtain a slight improvement of LOD agreement by about 1 μs in the standard deviations of LOD differences with those of CODE, IGS, and IERS C04 08 when troposphere gradients from CODE are introduced into the analyses of Intensive sessions (*Solution 2*).

4. Conclusions

At co-location sites with GNSS, we derived zenith wet delays and troposphere horizontal gradients at each VLBI observation epoch from GNSS CODE solution and introduced them in the analysis of VLBI Intensive sessions observed from the beginning of 2008 till the end of 2014. When we introduce CODE gradients a priori to the analyses of Intensive sessions, there is a linear effect of sum of total east gradients over the stations on ΔUT1 estimates of INT1 sessions (Wettzell–Kokee) of about 13 μs/mm and of about 11 μs/mm for INT2 sessions (Wettzell–Tsukuba). Compared to ΔUT1 values from IERS C04 08 series, there is no improvement for INT2 sessions in standard deviations when introducing external troposphere delays from GNSS CODE and only a small improvement in both biases and standard deviations for INT1 sessions, which is due to the fact that ΔUT1 values of the IERS C04 08 series heavily depend on ΔUT1 values from VLBI Intensive sessions derived without external delays.

We get the best agreement of LOD in standard deviation of differences between IGS LOD and the Intensive session solution when zenith wet delays are estimated and gradients from GNSS CODE are introduced in the analyses of INT2 Intensive sessions. We found a slight improvement of agreement in standard deviation of LOD differences between the Intensive session solution when gradients from CODE are used and GNSS solutions (CODE and IGS) for both INT1 and INT2 sessions. The improvement is as large as 1 μs. We do not see any additional significant improvement of LOD agreement when external zenith wet delays are introduced. In conclusion, we suggest that zenith wet delays should be estimated in the analysis of Intensive sessions and either troposphere gradients from the analyses of GNSS observations at co-location sites should be introduced or gradients should be estimated to improve the accuracy of ΔUT1 and LOD estimates of INT1 and INT2 sessions. An improved modeling of azimuthal asymmetries in the troposphere delays is essential for accurate ΔUT1 estimation from the observations of Intensive sessions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.asr.2015.07.032.

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