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ORIGINAL ARTICLE

Universal time from VLBI single-baseline observations during CONT08

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Abstract The IVS Intensive sessions are single-baseline, 1-h VLBI sessions carried out everyday in order to determine Universal Time (UT1). We investigate different possibilities to improve the results of such sessions. We do this investigation by extracting 2-h single-baseline sessions from the CONT08 data set. These are analysed like normal Intensives, and the results are compared to the results of the analysis of the full CONT08 data set. We find that tropospheric asymmetry is the major error source for the single-baseline sessions. It is possible to improve the accuracy of the estimated UT1 either by using accurate a priori tropospheric gradients or by estimating gradients in the data analysis.

Keywords VLBI · Universal Time · Earth rotation · Tropospheric gradients

1 Introduction

Accurate knowledge of the Earth Orientation Parameters (EOP) is important for all kinds of navigation on the Earth and in space. Good EOP predictions require accurate measurements of EOP to be available in near real-time, especially of Universal Time (UT1). The primary technique today for measuring UT1 is geodetic Very Long Baseline Interferometry (VLBI).

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Typically, two or three 24-h VLBI experiments dedicated to EOP estimation are carried out every week. These experiments involve up to eight worldwide distributed stations and the results are available about 2 weeks after the experiments. In order to have a more continuous monitoring of UT1 with shorter latency, special 1-h long single-baseline VLBI experiments are conducted everyday: the so-called Intensive VLBI experiments. These only use two (or sometimes three) VLBI stations and the stations used for the Intensives have varied over the years. The first Intensive sessions in the 1980s used the baseline Wettzell (Germany)–Westford (USA) (Robertson et al. 1985). Currently, mainly two baselines are used: on weekdays at ∼18:30 UT, the baseline Wettzell–Kokee Park (Hawaii, USA) is used (the INT1 sessions) and on weekends at ∼7:30 UT, the baseline Wettzell–Tsukuba (Japan) is used (INT2). In addition, on Mondays at 7:00 UT, the INT3 sessions are using the three stations Wettzell, Tsukuba, and Ny-Ålesund (Spitsbergen, Norway; Luzum and Nothnagel 2010). The results from the Intensives are currently available with a latency of 1 or 2 days, but by using e-transfer of the data from the telescopes to the correlator the results will become available in near real-time in the near future. The Fennoscandian-Japanese experiments between Onsala (Sweden), and Metsähovi (Finland), Tsukuba and Kashima (Japan) (Sekido et al. 2008) demonstrated that it is possible to provide UT1 estimates within 4 min after the end of an Intensive session (Matsuzaka et al. 2008). With UT1 soon being available in near real-time from the Intensives, the importance of these sessions for EOP prediction will increase (Luzum and Nothnagel 2010).

To make the best use of the UT1 results estimated from the Intensives, their accuracy should of course be as high as possible. Several studies have been performed in the past in order to evaluate the accuracy of the Intensives and investigate possible improvements (Robertson et al. 1985;

Ray et al. 1995; Hefty and Gontier 1997; Nothnagel and Schnell 2008; Böhm et al. 2010a). For example, Böhm et al. (2010a) investigated the possibility to use tropospheric slant delays obtained from numerical weather models in the data analysis, and they found a small improvement when this was done. A problem with evaluating the accuracy of the estimated UT1 is to have accurate UT1 measurements for comparison. Böhm et al. (2010a) used UT1 from the IERS 05 C04 series (Bizouard and Gambis 2009). This is far from optimal since the UT1 results estimated from the Intensive sessions are important ingredients for the production of the IERS 05 C04 series. The best option is probably to use UT1 estimated from simultaneous 24-h VLBI sessions for comparison. However, this cannot be done for all Intensives. For example, 24-h VLBI sessions on weekends, when the INT2 sessions are performed, are very rare.

In this work, we use another strategy to evaluate possible improvements to the Intensives. Instead of using the actual Intensives, we extract single-baseline observations from normal 24-h VLBI experiments. These extracted Intensive sessions are then processed in a similar approach as the standard Intensives. The results from the processing of the full 24-h VLBI data set do not only provide UT1 that can be used for comparison, but also other parameters (e.g. polar motion and tropospheric parameters) that can be used for the analysis of the extracted Intensive data. Another advantage of this strategy is that several different single-baselines can be investigated, not only those normally used for the Intensives. The disadvantage of this strategy is that a normal 24-h VLBI session schedule is not optimised to provide many observations on a particular baseline, thus we will most likely not get as many observations per hour for our extracted Intensive session as there are in a normal Intensive session. Furthermore, the geometry of the observations in the extracted Intensive sessions may not be optimal. Because of this, our extracted Intensive sessions probably give less accurate results than normal Intensives. However, the extracted Intensive sessions are still useful to evaluate possible analysis strategies for improving the accuracy of Intensive-like sessions.

The 24-h VLBI sessions used in this work are those of the continuous VLBI campaign CONT08. This was a VLBI campaign consisting of 15 days of continuous VLBI observations between August 12 to August 26, 2008. In total, 11 stations participated in this campaign (see Fig. 1), and the accuracy of the results should be on the level of what is possible to achieve with VLBI today. The processing of the data, both of the full CONT08 data set and the extracted Intensive sessions, is described in Sect. 2. The results are presented in Sect. 3. We investigate two possible error sources for the Intensives: tropospheric asymmetry (Sect. 3.1) and polar motion (Sect. 3.3). We also investigate the possible improvement from adding a third station to the Intensives (Sect. 3.2). The conclusions are presented in Sect. 4.

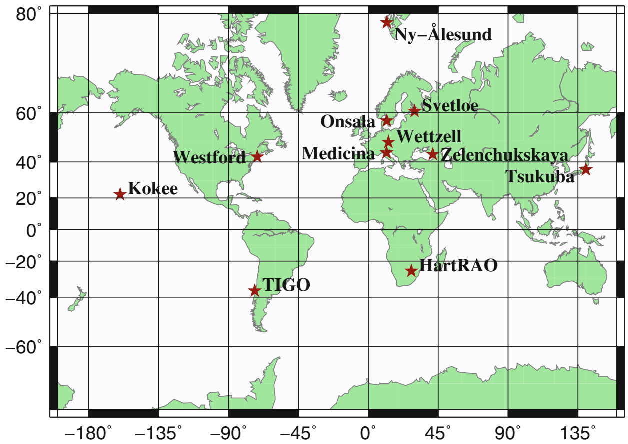

Fig. 1 The stations in the CONT08 network

2 Data analysis

The observed VLBI group delay, τ, can be expressed as (Nothnagel and Schnell 2008):

$$\tau \approx -\frac{1}{c}\mathbf{b}^T\, R_3(-\theta)\,\mathbf{k} + \tau_{\text{clock}} + \tau_{\text{tropo1}} - \tau_{\text{tropo2}} + \tau_{\text{other}} \quad (1)$$

where c is the speed of light in vacuum, $\mathbf{b} = [b_x, b_y, b_z]^T$ the baseline vector in the Terrestrial Intermediate Reference System (i.e. the baseline vector multiplied with the polar motion rotation matrix), $R_3(\theta)$ is the rotation matrix for the rotation of the Earth, θ is the rotation angle of the Earth, $\mathbf{k} = [k_x, k_y, k_z]^T$ the unit vector of the source in the Celestial Intermediate Reference System (i.e. the precession/nutation rotation matrix multiplied with the source vector), τ_{clock} is the clock difference between the stations, $\tau_{\text{tropo}i}$ is the tropospheric delay at station i, and τ_{other} is all other corrections and errors (tidal displacements, relativistic effects, instrumental noise, etc.). The partial derivative of τ w.r.t. UT1 is:

$$\frac{\partial\tau}{\partial \text{UT1}} = \frac{1}{c}(k_x[b_x \sin(\theta) + b_y \cos(\theta)] + k_y[-b_x \cos(\theta) + b_y \sin(\theta)])\frac{\partial\theta}{\partial \text{UT1}} \quad (2)$$

where $\partial\theta/\partial\text{UT1} = 1.00273781191135448$ (McCarthy and Petit 2004). From this equation, we can see that to have a high sensitivity to UT1 (i.e. large $\partial\tau/\partial\text{UT1}$), b_x and/or b_y should be large, i.e. the length of the projection of the baseline vector on the equatorial plane should be large. On the other hand, to have a good estimation of the various parameters (UT1, clock difference, tropospheric delay) in the VLBI data analysis, a uniform sky coverage is desired, but for long baselines the sources that can be observed at both stations cover only a small part of the skies above the stations. Thus, for accurate UT1 determination, the projection of the baseline on the equatorial plane should be long, but still short enough to allow for a relatively good sky coverage.

For the VLBI data analysis, we used the Vienna VLBI Software (VieVS) (Böhm et al. 2009). This is a new VLBI software developed at the Institute of Geodesy and Geophysics, Vienna University of Technology. It implements the latest IERS Conventions (McCarthy and Petit 2004) and the parameter estimation is performed using the classical least squares method.

The analysis of the full CONT08 data set is described in detail in Nilsson et al. (2010). We estimated the Zenith Wet Delays (ZWD) as piecewise linear functions in 30- min intervals, tropospheric gradients in 2-h intervals, clock offsets in 1-h intervals, and EOP in 1-h intervals. Relative constraints (rather loose) were applied to these parameters in order to stabilise the solution and avoid problems in time intervals with few observations for a station. The station coordinates were estimated applying no-net translation and no-net rotation relatively to VTRF2008 (Böckmann et al. 2010), and the source coordinates were fixed to ICRF2 (Fey et al. 2009). The normal equations of all 15 24-h sessions were stacked to obtain one normal equation system for the whole CONT08 period. Solving this gave continuous time series of ZWD, gradients, and EOP, as well as one set of station coordinates for the whole CONT08 period. In the solution, high frequency nutation and polar motion in the retrograde diurnal band were blocked using the method described in Nilsson et al. (2010).

To create the single-baseline sessions, we extracted all observations of a specific baseline in a 2-h interval from the full CONT08 data set. Two hours were used instead of 1 h (which is the usual length of an Intensive session) in order to increase the number of observations. We do not expect that the fact that the observations cover a 2-h time-span instead of just 1-h will have any significant effect on the results since most parameters estimated in the data analysis are not time dependent (all except the clock rate, see next paragraph). Examples of sky-plots for one extracted Intensive session (for the Wettzell–Tsukuba baseline) are shown in Fig. 2. For comparison, the sky-plots of an actual Intensive using this baseline are shown (the INT2 on August 23, 2008). We can see that the observations for both the extracted Intensive and the INT2 have relatively similar sky distributions, but the INT2 has more observations (32 observations for the INT2, 20 for the extracted Intensive). The baselines used, the baseline length, the length of the baseline projected on the equatorial plane, the longitude difference of the stations of the baseline, the number of sessions obtained for each baseline, and the average number of observations in one session are shown in Table 1. To have a high sensitivity to UT1, the projection of the baseline on the equatorial plane should be as long as possible (see Eq. 2). Typically, the number of scans per session is less than for a normal Intensive (about 25 scans). Only sessions with 10 or more observations were included in the analysis, thus the number of sessions obtained for different baselines varies. In addition to using only single-baseline sessions, we also investigated two networks with three stations (see Sect. 3.2), as well as the actual INT1 sessions (Wettzell–Kokee) observed during the CONT08 period.

The extracted Intensive sessions were processed in a similar way as standard Intensive sessions. For each session, we estimated a clock error (one offset and one rate, which was found to be a sufficient parameterisation in this case), ZWD for each of the two stations, and UT1. In addition, tests were made where we estimated tropospheric gradients or fixed the ZWD to a priori values (see Sect. 3.1). Unless otherwise noted, the station coordinates, polar motion, and nutation were fixed to the values estimated in the analysis of the full CONT08 data set. This was done in order to have consistent a priori values for these parameters, in order to better see the errors caused by other error sources. The source coordinates were fixed to ICRF2.

3 Results

3.1 Effects of tropospheric asymmetry

Normally, tropospheric gradients are not estimated in the data analysis of the Intensive sessions. The reason is that there is only a small number of observations in a typical Intensive session and the geometry of the observations may not be optimal for gradient estimation. Thus, singularity problems may occur if we try to estimate gradients. However, not estimating gradients will lead to errors in UT1 if large gradients are present. Böhm and Schuh (2007a) found that an unmodelled east gradient of 1 mm will cause an error in UT1 of about 15 µs. This is a significant error since gradients of several mm can occur, especially at stations with highly variable weather like Tsukuba (Böhm et al. 2010a).

Figure 3 shows the error in UT1 (i.e. the estimated UT1 minus the UT1 estimated from the full CONT08 data set) from two extracted Intensives: Wettzell–Tsukuba and Westford–Kokee. In the figure, the UT1 error is plotted as a function of the sum of the east gradients at the two stations (obtained from the full CONT08 solution). We can note that there seems to be a correlation between the UT1 error and the sum of the east gradient: the correlation coefficient is −0.38 for Wettzell–Tsukuba and −0.21 for Westford–Kokee. This shows that tropospheric gradients can cause significant errors in the UT1 estimates (although it is probably not the only significant error source). Fitting a straight line to the data, we find that the error in UT1 is −12 to −10 µs/mm total east gradient for both baselines as well as for most other single-baselines investigated in this work (formal errors of the slopes are typically 2–3 µs/mm).

In this work, we try several different strategies for reducing the error in UT1 caused by tropospheric gradients. The following strategies are investigated:

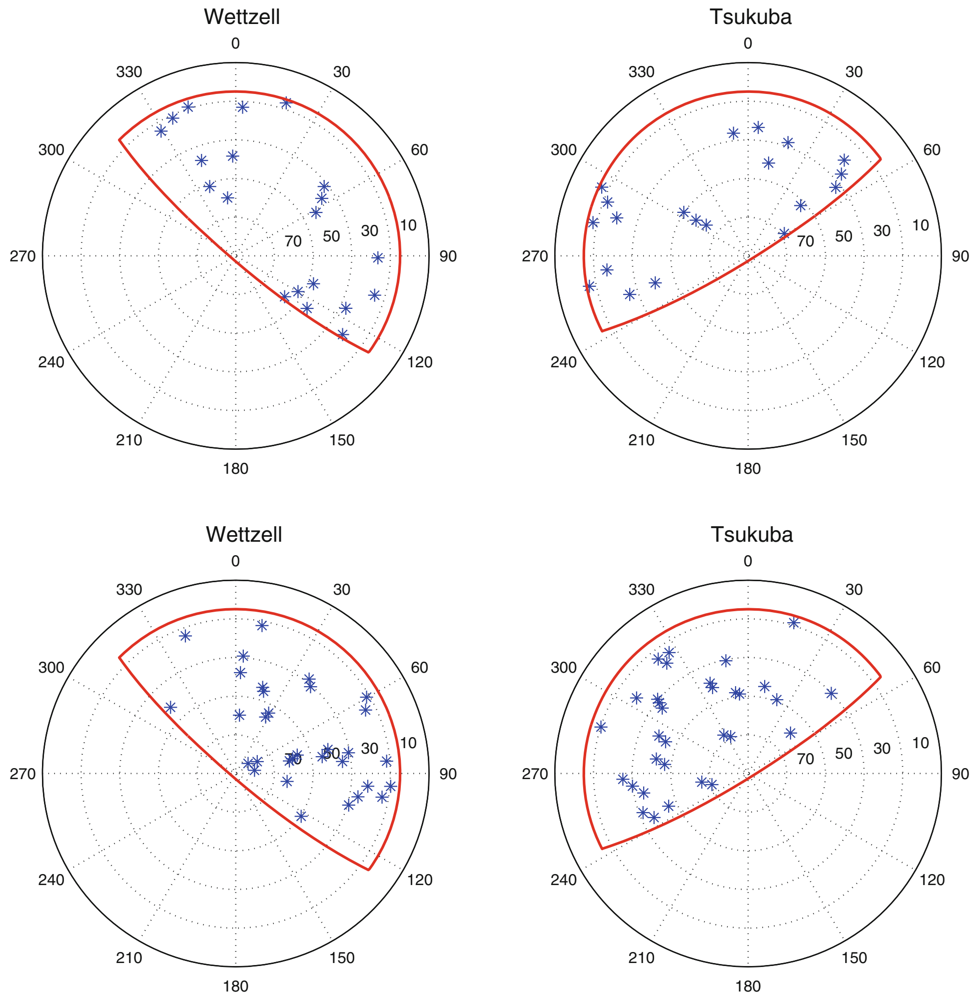

Fig. 2 Sky-plots of the observations from one single-baseline session (Wettzell–Tsukuba, August 18, 20–22 UT) (*top*) and from the INT2 session (Wettzell–Tsukuba) on August 23, 7:30-8:30 UT (*bottom*). The *red lines* shows the regions in which a source is visible at an elevation angle larger than 5° at both stations

Table 1 The 2-h single-baseline sessions extracted from the CONT08 data set

Baseline	Length (km)	Eq. proj. (km)	Long. span. (°)	# session	# scans/session
Wettzell–Tsukuba	8,445	8,378	127	130	16.2
Wettzell–Kokee	10,357	10,072	173	104	12.3
Wettzell–Westford	5,998	5,977	84	163	19.2
Wettzell–HartRAO	7,832	2,009	15	150	16.4
Onsala–Tsukuba	7,940	7,775	128	148	16.9
Medicina–Tsukuba	8,781	8,752	128	126	15.1
Ny-Ålesund–Tsukuba	6,498	5,998	128	164	24.0
Tsukuba–Kokee	5,755	5,594	60	167	30.3
Westford–Tsukuba	9,506	9,489	148	118	13.8
Westford–Kokee	7,676	7,435	88	166	20.4
INT1	10,357	10,072	173	10	23.1
Wettzell, Tsukuba, Ny-Ålesund	–	–	–	116	14.7
Wettzell, Westford, Ny-Ålesund	–	–	–	142	15.7

Shown are the baseline length, the length of the baseline projected on the equatorial plane, the longitudinal span, number of extracted sessions, and average number of scans per session

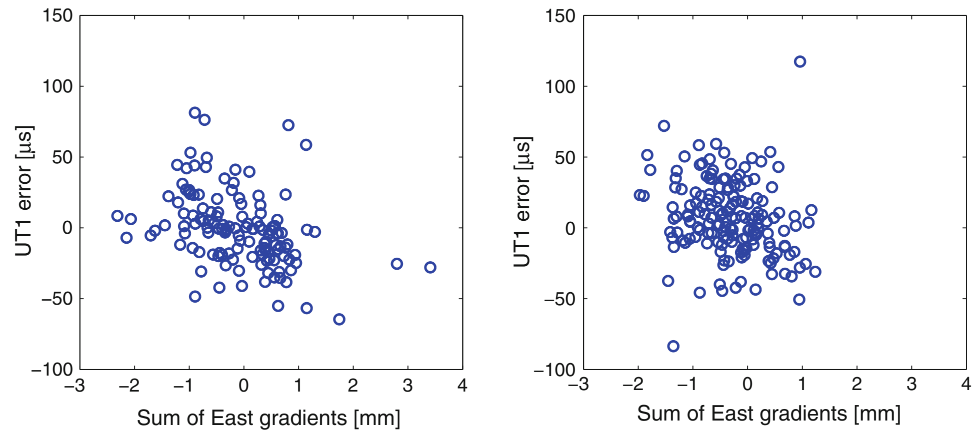

Fig. 3 The error in UT1 estimated from the extracted Intensive sessions, as function of the sum of the east gradients at the two stations. *Left plot* is for the baseline Wettzell–Tsukuba, *right* is for Westford–Kokee

- *Standard solution*: standard Intensive data analysis (estimate ZWD but fix gradients to zero).
- *Extended solution*: also estimate tropospheric gradients in the data analysis. In order to avoid possible singularity problems, the gradients were constrained to zero (±1 mm).
- *Fix gradients solutions*: like standard solution, but gradients are fixed to the values estimated in the analysis of the full CONT08 data set.
- *Fix ZWD solution*: the ZWD are not estimated but fixed to the values estimated in the analysis of the full CONT08 data set. Gradients fixed to zero.
- *Fix troposphere solution*: both ZWD and gradients are fixed to the values estimated in the analysis of the full CONT08 data set.
- *ECMWF gradients solution*: like standard solution, but gradients are fixed to the values estimated from ECMWF (European Centre for Medium-range Weather Forecasts) data (Böhm and Schuh 2007b) (ZWD estimated).

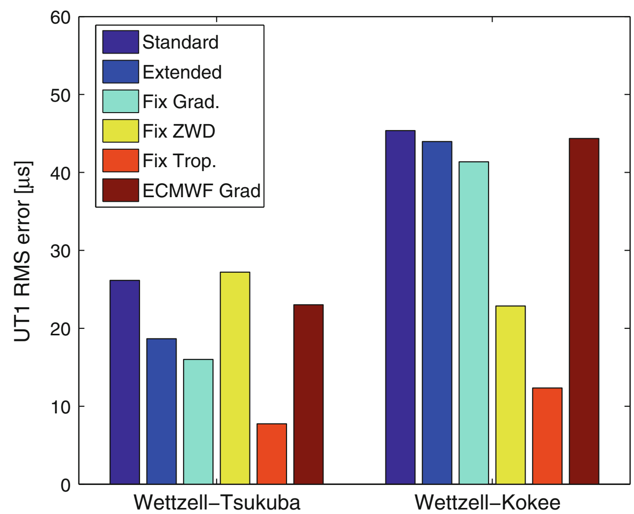

Fig. 4 RMS differences of UT1 estimated from the extracted Intensive sessions and UT1 from the full CONT08 data set. Shown are the results of five different solutions: fixing gradients to zero (Standard), estimating gradients in the data analysis (Extended), fixing gradients to a priori values (Fix grad.), fixing ZWD to a priori values and gradients to zero (Fix ZWD), fixing both ZWD and gradients to a priori values (Fix trop.), and fixing gradients to those estimated from ECMWF data (ECMWF grad.)

Figure 4 shows the RMS (Root-Mean-Square) of the difference in UT1 estimated by the analysis of the extracted Intensive sessions and the UT1 estimated from the full CONT08 set. The results for two baselines are shown: Wettzell–Tsukuba and Wettzell–Kokee. In general, the RMS for Wettzell–Kokee is larger than for Wettzell–Tsukuba. This is most likely due to the fact that the Wettzell–Kokee baseline in general has fewer observations (see Table 1) with a worse sky coverage (since the baseline is longer). For Wettzell–Tsukuba, there is a clear improvement when using a priori gradients. Estimating gradients in the data analysis also gives a significant improvement. However, for Wettzell–Kokee, the improvement is not as large when estimating or using a priori gradients. One reason could be that the gradients at Kokee are smaller than in Tsukuba; thus, gradients are not an important error source for this baseline. As seen in Teke et al. (2010), the gradients at Tsukuba during CONT08 are larger and more variable than at the other stations. Another reason is that there are generally very few observations for the Wettzell–Kokee sessions; thus, the sensitivity to observation noise is higher. Fixing all tropospheric parameters (ZWD and gradients) to the results of the CONT08 network analysis improves the UT1 results on both baselines. However, when fixing only ZWD to the results of the CONT08 network analysis, the UT1 results on the baseline Wettzell–Tsukuba get slightly worse, compared to the standard analysis. The likely reason is that the gradients are absorbed to some extent in the ZWD estimates in the standard solution; thus, the impact of the gradients on UT1 will be larger if ZWD is fixed.

A comparison between the east gradients estimated from the extracted Intensive sessions and those from the full

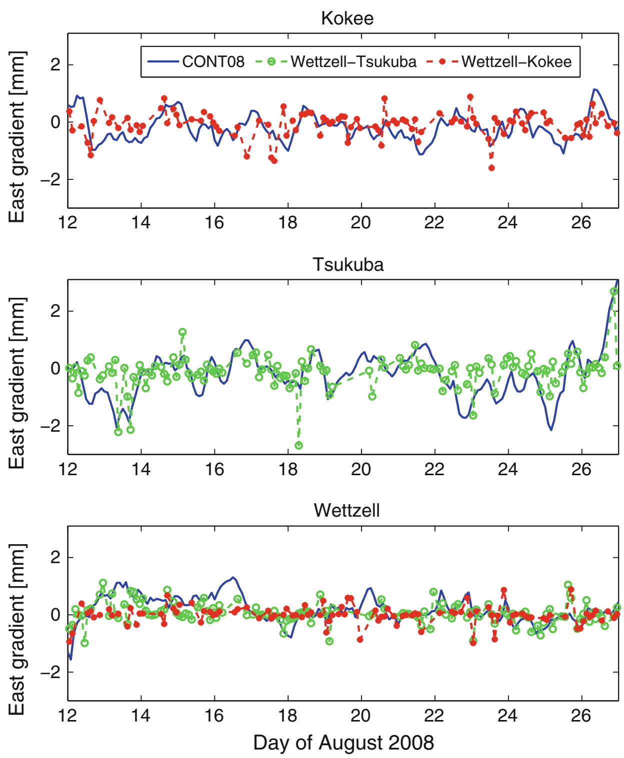

Fig. 5 East gradients estimated from the CONT08 data and from two extracted Intensive sessions (Wettzell–Tsukuba and Wettzell–Kokee)

CONT08 analysis is shown in Fig. 5. We can see that there is a decent agreement between the gradients. The agreement between north gradients estimated from the extracted Intensives and the full CONT08 data set is on a similar level. It should be noted that when estimating gradients, the correlation between the errors in the east gradients and the UT1 error is rather significant. The correlation coefficient between the error in the sum of the east gradients at the two stations and the error in UT1 is on average 0.40 for Wettzell–Tsukuba and 0.47 for Wettzell–Kokee. Thus, in some cases, it will be difficult to separate UT1 and the east gradients in the data analysis, especially when the number of observations is low. In these situations, we would expect the estimated east gradients to be close to zero and the UT1 estimates to those estimated in the standard solution (since we apply absolute constraints to the gradients in the data analysis, but not to UT1). This is the likely explanation for why the gradients for Wettzell from the Wettzell–Kokee solution are smaller than those from the Wettzell–Tsukuba solution (see Fig. 5), and could also explain why estimating gradients do not improve the accuracy of UT1 from the Wettzell–Kokee baseline.

The biases and RMS errors of UT1 estimated from the extracted single-baseline sessions, relative to the UT1 series from the full CONT08 data set, are shown in Table 2. In general, the biases are small and insignificant. The RMS errors generally decrease when gradients are estimated or a priori gradients from the full CONT08 solution are used. This is particularly true for the baselines including station Tsukuba, thus further indicating that gradients are an important error source when this station is involved. As discussed above, Tsukuba is the station in CONT08 which has the largest gradients.

The lowest UT1 RMS errors are generally obtained for the baselines between Tsukuba and the European stations, being for instance as small as 7.8 µs in the optimal case (Wettzell–Tsukuba, fix troposphere solution). The reason is that the length of this baseline projected on the equatorial plane is relatively large (which is good for accurate UT1 determination from an Intensive, see Sect. 2), while still having a relatively high number of observations (see Table 1). Baselines with fewer observations (e.g. Wettzell–Kokee) or of shorter length (e.g. Tsukuba–Kokee) have larger RMS. The largest RMS are found for the Wettzell–HartRAO baseline. This is a nearly North–South baseline, thus not very sensitive to UT1.

When using a priori gradients estimated from ECMWF data, the RMS errors decrease slightly relatively to the standard solution, but the absolute values of the biases generally get larger (on average by 2.8 µs). The RMS errors are however still clearly larger than when using the gradients from the CONT08 analysis as a priori, and for most cases they are also larger than the RMS errors obtained when estimating gradients in the data analysis.

We have also analysed the INT1 sessions that were observed during the CONT08 period, and the results are also shown in Table 2. For these sessions, there are only minor differences between the results obtained using the different strategies. The main difference is in the bias, where a decrease in the bias can be seen when a priori ZWD and/or gradients are used. It should, however, be noted that there were only 10 INT1 sessions during the CONT08 period, which is not enough to draw any definite conclusions. Furthermore, since there are no observations for Wettzell and Kokee in the CONT08 data set during the periods when the INT1 sessions were observed, the accuracy of the ZWD and the gradients estimated for these stations during these time periods are likely to be worse than for other periods.

3.2 Adding a third station

We also investigated the effect of adding a third station. Two networks with three stations were investigated: Wettzell, Tsukuba, and Ny-Ålesund, as well as Wettzell, Westford, and Ny-Ålesund. For these sessions, we only included scans where all three stations participated; thus, the number of scans for these sessions is even lower than for the single-baseline sessions. The results, using the same estimation strategies as presented in Sect. 3.1, are presented in Table 3. We compared the results of the three-station networks to the

Table 2 Biases and RMS errors (relative to the CONT08 solution) of UT1 estimated from the extracted Intensive sessions

Baseline	Standard solution	Extended solution	Fix grad.	Fix ZWD	Fix trop	ECMWF grad.
Wettzell–Tsukuba	−0.7 ± 26.2	−0.9 ± 18.7	1.7 ± 16.0	−6.2 ± 27.2	0.4 ± 7.8	3.9 ± 23.0
Wettzell–Kokee	6.6 ± 45.4	3.7 ± 44.0	4.9 ± 41.4	6.0 ± 22.9	−0.1 ± 12.3	9.9 ± 44.4
Wettzell–Westford	7.5 ± 37.0	2.1 ± 29.9	1.2 ± 27.4	16.1 ± 36.4	1.2 ± 12.2	4.9 ± 30.6
Wettzell–HartRao	−1.8 ± 75.1	−6.8 ± 63.7	−9.0 ± 64.8	5.4 ± 74.8	0.1 ± 44.7	−19.8 ± 69.7
Onsala–Tsukuba	−3.6 ± 32.6	−2.0 ± 29.0	−0.9 ± 22.2	−3.9 ± 31.3	−1.6 ± 12.4	1.6 ± 32.2
Medicina–Tsukuba	0.5 ± 32.7	−2.4 ± 31.0	−0.9 ± 21.8	6.2 ± 34.6	−0.4 ± 11.2	1.6 ± 30.5
Ny-Ålesund–Tsukuba	2.3 ± 23.3	−1.6 ± 16.2	−1.2 ± 14.1	3.0 ± 28.1	−1.0 ± 10.5	4.8 ± 21.3
Tsukuba–Kokee	11.7 ± 50.9	4.0 ± 44.2	−2.1 ± 42.2	10.9 ± 38.7	0.1 ± 22.1	17.8 ± 51.8
Westford–Tsukuba	3.4 ± 28.4	0.0 ± 22.3	−1.1 ± 21.4	7.7 ± 25.6	−1.6 ± 13.3	3.3 ± 26.3
Westford–Kokee	7.1 ± 26.8	7.2 ± 26.5	2.5 ± 20.5	5.0 ± 27.6	1.5 ± 15.0	5.2 ± 24.7
INT1	16.2 ± 22.7	16.3 ± 22.8	13.8 ± 22.5	8.8 ± 26.2	6.4 ± 24.4	16.1 ± 22.5

All values are in µs

Table 3 Bias and RMS errors (relative to the CONT08 solution) of UT1 estimated from extracted Intensive sessions with three stations

Baseline	Standard solution	Extended solution	Fix grad.	Fix ZWD	Fix trop.
Wettzell, Tsukuba, Ny-Ålesund	1.5 ± 25.2	−1.6 ± 16.2	1.5 ± 14.6	−2.7 ± 25.9	−0.5 ± 8.5
Wettzell, Tsukuba	3.2 ± 26.7	0.5 ± 18.9	3.1 ± 16.4	−5.1 ± 26.7	0.7 ± 8.9
Wettzell, Ny-Ålesund	8.1 ± 73.9	11.7 ± 63.2	12.5 ± 60.7	−23.2 ± 48.9	−1.5 ± 22.6
Tsukuba, Ny-Ålesund	6.7 ± 37.9	1.5 ± 28.2	2.7 ± 28.2	5.0 ± 32.1	−2.5 ± 12.3
Wettzell, Westford, Ny-Ålesund	3.4 ± 23.8	3.2 ± 18.0	2.1 ± 19.6	11.5 ± 25.8	2.2 ± 10.9
Wettzell, Westford	−2.5 ± 41.6	−0.8 ± 31.1	−1.3 ± 34.1	18.9 ± 40.4	1.5 ± 13.3
Wettzell, Ny-Ålesund	4.4 ± 45.2	4.4 ± 41.2	0.7 ± 43.5	1.6 ± 53.3	−2.9 ± 22.5
Westford, Ny-Ålesund	7.1 ± 35.1	7.2 ± 31.0	6.1 ± 32.6	8.1 ± 29.0	5.7 ± 16.3

All values are in µs

results obtained when using only two of the three stations. For the latter, we still only included scans where all three stations participated; hence, the results obtained for these baselines are different from those presented in Table 2. For both three-station networks, there is an improvement when using three stations compared to only using two. This improvement is significant for the network Wettzell, Westford, and Ny-Ålesund, where the RMS values decrease by over 10 µs relatively to the best single-baseline (except when fixing ZWD). However, for the network Wettzell, Tsukuba, and Ny-Ålesund, there is only a small improvement compared to using only Wettzell and Tsukuba. The decreases in the RMS values are less than 3 µs. The likely reason is that the sensitivity to UT1 is much larger for the observations made on the Wettzell–Tsukuba baseline than for the observations involving Ny-Ålesund, as the East–West extensions of these baselines are shorter.

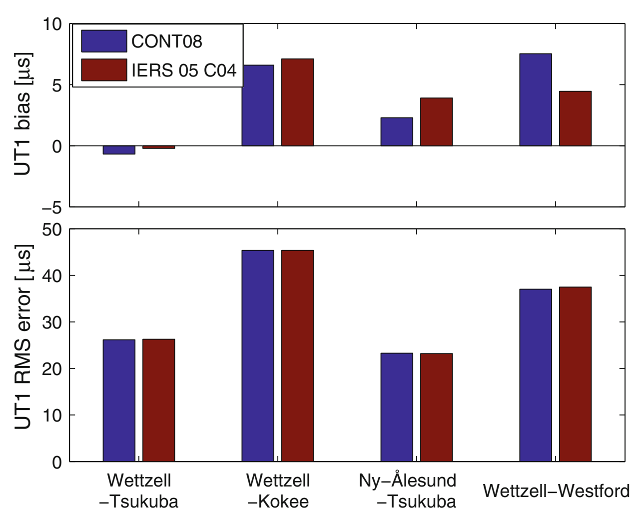

Fig. 6 Biases and RMS errors of the UT1 estimated from the extracted Intensive sessions. Shown are the cases where polar motion and nutation are obtained from the CONT08 results, and when the IERS 05 C04 values are used

3.3 Effects of polar motion

Figure 6 shows the effect on UT1 estimated from the single-baseline sessions when the a priori polar motion and nutation is taken from the IERS 05 C04 series together with the IERS recommended model for high frequency polar motion variations (McCarthy and Petit 2004), instead of entering the results from the analysis of the full CONT08 sessions. The effect is small. There are small changes in the biases, while the RMS is hardly affected at all. However, if we would have used a priori EOP with a much lower accuracy than IERS 05 C04 and a longer time span than only 15 days, the impact would be more significant, as discussed by Nothnagel and Schnell (2008).

Another important error source related to EOP is the model for high frequency EOP variations. According to Böhm et al. (2010b), the error in UT1 caused by errors in the high frequency EOP model can reach up to 15 µs. In this work, this error is not investigated. Since we did not use any sub-daily EOP model, we are not sensitive to errors in such models (our a priori polar motion and reference UT1 are both from the full CONT08 solution, having 1-h resolution and containing all sub-diurnal variations).

4 Conclusions

The CONT08 campaign provided the opportunity to create single-baseline and three-baseline subsets and thus extract Intensive type sessions. However, unlike the normal situation, precise measurements of EOP and other parameters are available from the analysis of the full CONT08 network that can be used as an external reference. This allows to derive interesting conclusions.

The results show that atmospheric gradients can be a significant error source for the Intensive sessions. This is particularly true if stations with a highly variable troposphere, like Tsukuba, are included. The gradients mainly cause an increase in the RMS error, while the bias is not affected that much. The reason is probably that the mean (east) gradients over the investigated period are close to zero, thus causing no significant biases. If good a priori gradients are used, the results can be improved significantly; however, the problem is how to get a priori gradients with high enough accuracy. For a typical Intensive session, there are no simultaneous 24-h VLBI sessions which can provide gradients. In this work, we investigated the use of gradients from ECMWF. In general, this improves the results, but only slightly. One other possibility could be to use gradients estimated from GPS. All VLBI stations are co-located with a GPS station, and the GPS processing could in principle be done in near real-time to provide gradients. It should be further investigated if gradients from GPS are accurate enough to be used in the analysis of Intensive sessions.

If no accurate a priori gradients are available, the results can still be improved by including the estimation of gradients in the data processing. The accuracy of UT1 estimated using the Wettzell–Tsukuba baseline is clearly improved relatively to the standard solution when estimating gradients. No improvement is seen for the Wettzell–Kokee baseline when estimating gradients, but this may be due to the fact that the extracted Intensives for this baselines have few observations (on average 12.3). However, this strategy of estimating gradients in the data analysis of the Intensives should be revisited when using real Intensive sessions. First results of such an investigation were presented by Böhm et al. (2010b). They found an improvement in the length-of-day estimates w.r.t. to those estimated from GPS when including the estimation of gradients in the processing of the INT2 sessions.

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