Tropospheric Modeling for the Intensive Sessions

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Abstract We investigate different possibilities for improving the modeling of the tropospheric delays in the data analysis of the Intensive VLBI sessions. These possibilities include using external information from GNSS or ECMWF, as well as extending the parametrization in the data analysis by also estimating tropospheric gradients or constraining the tropospheric variations using a turbulence model. In general, the results show that estimating gradients in the data analysis improves the results. The best strategy, however, depends on the type of Intensive session and the quality of the a priori tropospheric data.

Keywords VLBI, Intensives, troposphere, UT1

1 Introduction

The Intensive VLBI sessions are VLBI sessions performed approximately every day in order to monitor UT1–UTC. In most cases just two stations on a long East-West baseline are used, and the sessions are only one-hour long. Because of this, the number of observations is rather low (20–30), and the geometrical distribution of the observed radio sources on the skies above the stations is relatively poor. This limits the number of parameters that can be estimated in the data analysis of these sessions. Normally, just clock offsets, clock drifts, one constant zenith wet delay (ZWD) per station, and one UT1–UTC offset are estimated. In particular for the troposphere this parametrization may not be sufficient, e.g., the tropospheric gradients are not estimated but fixed to a priori values. Hence, if large tropospheric gradients are present, these will lead to errors in the analysis results, e.g., in the UT1–UTC estimates.

The tropospheric modeling of Intensive sessions was investigated by Nilsson et al. (2011) [6]. They created Intensive-like sessions by extracting single-baseline observations from the CONT08 data set. They found that, if good a priori information about the troposphere is available, the accuracy of the UT1–UTC estimates improves. Furthermore, they also found an improvement if tropospheric gradients were estimated in the data analysis. This improvement was confirmed for the actual Intensive sessions by Böhm et al. (2010) [2].

In this work we investigate different possibilities for the modeling of the troposphere in the data analysis of the Intensives. We test using a priori information of the troposphere estimated from GNSS (Global Navigation Satellite Systems) or ECMWF (European Centre for Medium-range Weather Forecasts) analysis data. Furthermore we also consider the possibility of extending the tropospheric modeling in the data analysis, e.g. by estimating also tropospheric gradients or by modeling the tropospheric delays using a turbulence model.

2 The Intensive Sessions

In this work we analyzed the data from the 2012–2013 Intensive sessions. We considered three different types

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Table 1 The different types of Intensives used in this work. The table gives the baselines, the observation time, the baseline length, and the length of the baseline projected onto the equatorial plane.

	Stations	Observation time	Baseline length [km]	Equatorial proj. [km]
INT1	Wettzell, Kokee Park (Svetloe, occasionally)	Monday–Friday	10357	10072
INT2/INT3	Wettzell, Tsukuba (Ny-Ålesund, INT3) (Sheshan, occasionally)	Weekends Monday (INT3)	8445	8378
Ru-U	Zelenchukskaya, Badary (Svetloe, occasionally)	Every day	4405	4364

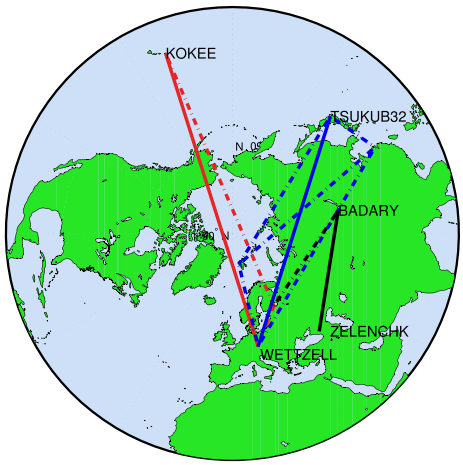

Fig. 1 The baselines observed in the Intensive sessions used in this work. Shown are the INT1 (red), the INT2/3 (blue), and the Ru-U (black) baselines. Solid lines are baselines included in most sessions, and dashed lines denote baselines only occasionally used.

of Intensive sessions, which are presented in Table 1. The baselines of these sessions are plotted in Figure 1.

3 Data Analysis

The data were analyzed with the Vienna VLBI Software (VieVS, [1]). In the data analysis we estimated clock offsets, linear clock drifts, and UT1–UTC. For the troposphere we tested several different parametrizations, as listed below. Unless otherwise noted, one ZWD per station was estimated.

Standard Tropospheric gradients fixed to zero.

DAO grad. Tropospheric gradients fixed to constant station-wise values derived from data of the Goddard Data Assimilation Office (DAO) [5].

ECMWF grad. Tropospheric gradients fixed to values derived from ECMWF operational analysis data [3].

GNSS grad. Tropospheric gradients fixed to the GNSS estimates (the IGS (International GNSS Service) tropospheric product [4])

GNSS trop. Both ZWD and tropospheric gradients taken from the IGS tropospheric product. No ZWD estimated in the data analysis.

Est grad. Tropospheric gradients were estimated in the data analysis. These were constrained to the DAO values using a σ of 1 mm.

Turbulence One tropospheric delay per station was estimated for every scan. These were constrained with a variance-covariance matrix estimated using turbulence theory (Treuhaft and Lanyi, 1987 [9]).

For the *turbulence* solution, the variance-covariance matrix was calculated assuming that the fluctuations in the refractive index, n, between $\mathbf{r}_1$ and $\mathbf{r}_2$ can be expressed by the structure function:

$$\left\langle [n(\mathbf{r}_1) - n(\mathbf{r}_2)]^2 \right\rangle = C_n^2 \frac{|\mathbf{r}_1 - \mathbf{r}_2|^{2/3}}{1 + \left[\frac{|\mathbf{r}_1 - \mathbf{r}_2|}{L}\right]^{2/3}} \quad (1)$$

where C_n^2 is the refractive index structure constant and L is the saturation scale length. Station specific C_n^2 values were estimated from GNSS data (Nilsson et al., 2010, [7]). For the temporal variations we assumed the frozen flow hypothesis, i.e., that the fluctuations are moving with the wind. Since no precise wind information was available for the stations, we calculated variance-covariance matrices for 18 different

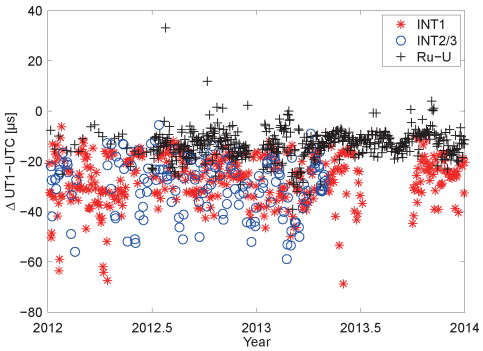

Fig. 2 The UT1–UTC error that would be caused by an unmodeled 1 mm East gradient at all stations in the 2012–2013 Intensive sessions.

wind vectors (velocity varied between 5 m/s and 15 m/s in steps of 5 m/s, direction between 0° and 300° in steps of 60°), and then calculated the average variance-covariance matrix.

As a reference solution we analyzed all IVS-R1, IVS-R4, IVS-T2, and RDV sessions from 2012–2013. In the analysis we estimated all five EOP (for polar motion and UT1–UTC one offset and one rate per EOP, and for nutation one offset for each component).

4 Results

We first investigated which UT1–UTC errors could be caused by unmodeled tropospheric gradients. This was done by changing the a priori East gradients of all stations by 1 mm in the standard solution, and then we checked what impact this had on the UT1–UTC estimates. The results can be seen in Figure 2. On average, the gradients cause a UT1–UTC error of −26.9 μs for the INT1 sessions and −27.7 μs for the INT2/3 sessions. This agrees with the results of Nilsson et al. (2011) [6], who found that the UT1-UTC error is −24 μs to −20 μs for a mean unmodeled East gradient of 1 mm. However, for the Ru-U sessions, the sensitivity to unmodeled gradients is lower; on average, the UT1–UTC error is 12.9 μs. The reason is probably because of different scheduling options being used for the Ru-U sessions compared to the INT1 and INT2/3 sessions. In particular, the Ru-U sessions generally make observations at higher elevation angles. For most of the Ru-U sessions the lowest elevation angle is 18° or larger, while for the INT1 and INT2/3 sessions it is between 5° and 10°. Since the effect of gradients is larger for low elevation angles, it is not surprising that the impact of gradients on the Ru-U results is lower.

Table 2 WM and WRMS differences between UT1–UTC values estimated from the Intensives and those from the reference solution.

	INT1		Ru-U	
Solution	WM [μs]	WRMS [μs]	WM [μs]	WRMS [μs]
Standard	3.0	20.7	21.9	45.0
DAO grad.	2.0	20.7	20.8	45.0
ECMWF grad.	2.4	20.7	21.5	45.2
GNSS grad.	−0.8	20.2	23.7	45.7
GNSS trop.	−0.4	21.2	25.4	44.5
Est. grad.	2.6	20.2	21.2	45.3
Turbulence	2.5	20.2	30.5	52.7

In Table 2 the weighted Mean (WM) and Weighted Root-Mean-Square (WRMS) differences between the different Intensive solutions and the reference solution are shown. These were calulated using all Intensives observed within one of the sessions of the reference solution. Since none of the sessions of the reference solution took place on weekends (nor Monday mornings), only the results for the INT1 and Ru-U sessions are shown. Mostly there are only minor differences between the different solutions. For the INT1 sessions the lowest WRMS values are obtained when fixing the gradients to the GNSS estimates, or when using an extended modeling in the data analysis (estimating gradients or using a turbulence model). For the Ru-U sessions, however, the turbulence model clearly gives the worst results. One reason could be that the Ru-U sessions normally do not include observations at low elevation angles. Thus, it is not possible to extend the parametrization for the troposphere. For the Ru-U sessions, there are relatively high WM values (around 20 μs).This is likely caused by inconsistencies in the station coordinates.

Using the UT1 values estimated from Intensives occurring on consecutive days we calculated daily length of day (LOD) values. We then compared these to LOD estimated by GNSS. The WM and WRMS differences can be seen in Table 3. The best results (lowest WRMS values) are here obtained when using gradients from GNSS (INT1), when estimating gradients in the data analysis (INT2/3), and when simply using the DAO gradients (Ru-U). However, here also the differences between the solutions are small. The exceptions are

Table 3 WM and WRMS differences between LOD values estimated from the Intensives and those from GNSS.

	INT1		INT2/3		Ru-U	
Solution	WM [μs]	WRMS [μs]	WM [μs]	WRMS [μs]	WM [μs]	WRMS [μs]
Standard	3.4	23.7	−0.7	20.7	1.6	53.1
DAO grad.	3.4	23.9	−0.8	20.5	1.6	53.0
ECMWF grad.	3.9	23.2	−0.5	20.0	1.7	54.1
GNSS grad.	3.1	22.2	−1.2	21.2	1.5	53.5
GNSS trop.	3.3	23.5	3.0	25.9	2.3	53.3
Est. grad.	3.5	23.3	−1.9	18.5	2.0	52.8
Turbulence	3.7	23.2	−2.3	18.6	2.4	62.3

for the turbulence model with the Ru-U sessions (see above), and when fixing all tropospheric parameters to the GNSS estimates for the INT2/3 sessions (probably because of biases in the GNSS ZWD estimates).

5 Conclusions

As we have seen, tropospheric gradients can—if not properly modeled in the data analysis—cause significant errors in the estimated UT1–UTC values. One way of reducing the impact of the gradients is to increase the elevation cut-off angle, like what is done for the Ru-U sessions. However, this makes the geometrical configuration worse, which will generally increase the uncertainty of the estimated parameters and the correlation between them. As seen in Tables 2 and 3, the WRMS values from the Ru-U sessions are higher than for the INT1 and the INT2/3 sessions, although this is also partly due to much shorter baselines being observed in the Ru-U sessions.

External tropospheric gradients from ECMWF or GNSS improve the results in some cases, but not always. Probably the accuracy of the external gradients varies from station to station; thus, whether or not the results are improved by external gradients depends on which stations are included in the Intensive sessions. Good quality of the external information is particularly important if also the ZWD are fixed to a priori values. In principle, because this reduces the number of unknown parameters, it should improve the precision. However, if there are systematic errors in the external ZWD values, the errors in the UT1–UTC estimates will increase. This is clearly the case for the INT2/3 sessions when fixing the tropospheric parameters taken from the IGS (Table 3).

Improving the tropospheric modeling by estimating more tropospheric parameters can improve the results. However, it is then important that the geometrical distribution of the observations be good enough to allow a separation of the different estimated parameters in the data analysis. This seems to be a problem when applying the turbulence model for the Ru-U sessions, while for INT1 and INT2/3 this strategy works well. For all session types the estimation of gradients in the data analysis gives satisfactory results. Thus, it is recommended that this strategy should be used when analyzing the Intensive sessions.

Acknowledgements

We would like to thank The International VLBI Service for Geodesy and Astrometry (IVS) [8] for providing the VLBI data used in this work.

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