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Impact of seasonal station motions on VLBI UT1 intensives results

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Abstract UT1 estimates obtained from the very long baseline interferometry (VLBI) Intensives data depend on the station displacement model used during processing. In particular, because of seasonal variations, the instantaneous station position during the specific intensive session differs from the position predicted by the linear model generally used. This can cause systematic errors in UT1 Intensives results. In this paper, we first investigated the seasonal signal in the station displacements for the 5 VLBI antennas participating in UT1 Intensives observing programs, along with the 8 collocated GPS stations. It was found that a significant annual term is present in the time series for most stations, and its amplitude can reach 8 mm in the height component, and 2 mm in horizontal components. However, the annual signals found in the displacements of the collocated VLBI and GPS stations at some sites differ substantially in amplitude and phase. The semiannual harmonics are relatively small and unstable, and for most stations no prevailing signal was found in the corresponding frequency band. Then two UT1 Intensives series were computed with and without including the seasonal term found in the previous step in the station movement model. Comparison of these series has shown that neglecting the seasonal station position variations can cause a systematic error in UT1 estimates, which can exceed 1 μs, depending on the observing program.

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1 Introduction

Very long baseline interferometry (VLBI) has been the principal method for the determination of Universal Time (UT1). The most accurate UT1 estimates can be obtained, simultaneously with other Earth rotation parameters (EOP) and terrestrial and celestial pole coordinates from 24-h VLBI sessions carried out on global networks of several, currently 7–9, stations. Their precision and accuracy depend on factors such as the number of stations, network geometry, and registration mode, see, e.g., Malkin (2009). However, the results of these observations are usually available only 8–15 days after observations, and besides these sessions are performed, on average, 2–3 times per week, which in addition affects these applications.

To get more frequent and timely UT1 estimates, several special observing programs are scheduled in the framework of the International VLBI Service for Geodesy and Astrometry (IVS) activity (Schlüter and Behrend 2007). These sessions, called Intensives, are carried out daily on one or two baselines, have 1-h duration, mostly employ electronic data transfer (e-VLBI), and hence provide rapid turnaround time from several hours to 2 days. Due to the short session duration (usually 1 h) and poor network geometry, only a limited number of parameters can be effectively estimated from these observations. Generally, this includes only UT1, station clocks offsets, and zenith troposphere delays. Thus, UT1 Intensives results decisively depend on many priori parameters used during Intensives data processing, such as pole coordinates and nutation model (Hefty and Gontier 1997; Titov 2000; Nothnagel and Schnell 2008; Malkin 2010a, 2011b), as well as on the station displacement model. In this paper, we concentrate on the latter.

The UT1 estimates depend on the length and the direction of the baseline, primarily on its equatorial projection. More accurate computation shows that the polar baseline projection has a small indirect impact on UT1 too (Nothnagel and Schnell 2008). The baseline length and direction do not remain constant, but vary due to numerous geophysical phenomena. Some effects such as plate motion and position jumps due to natural or instrumental reasons are accounted for in the TRF model, e.g., ITRF2008 (Altamimi et al. 2011). Others like solid earth and ocean tides, atmosphere and ocean loading, and antenna thermal deformation are included in the conventional observation reduction model, currently IERS Conventions (2010) (Petit and Luzum 2010). However, some effects that cause the station seasonal displacement are not always modelled properly, which can lead to errors in the data processing results. In particular, Malkin et al. (2012) suggested that non-linear station motions, in particular, seasonal station displacement, can cause systematic errors in the EOP estimates derived from single observing sessions processed using a linear station position model.

Numerous studies showed the presence of a millimeter-level seasonal signal in many VLBI and GPS station position time series, see Langbein and Johnson (1997), Titov and Yakovleva (2000), Blewitt et al. (2001), Malkin and Voinov (2001), van Dam et al. (2001), Dong et al. (2002), Petrov and Ma (2003), Petrov and Boy (2004), MacMillan and Boy (2004), Ding et al. (2005), Collilieux et al. (2007), Flouzat et al. (2009), Tesmer et al. (2009), van Dam et al. (2012). Almost all these papers are devoted to analysis of the height displacements, which generally prevails in the seasonal components of the station movements. However, the horizontal components of the displacement can also be significant (Petrov and Boy 2004; Flouzat et al. 2009).

In this paper, we studied the seasonal signal in the station displacements for the five VLBI antennas participating in the four main IVS UT1 Intensives observing programs. The displacement of the collocated GPS stations were also considered to estimate a site-specific seasonal signal in the movement of the stations belonging to the site. If this effect prevails over the station-specific phenomena, the GPS data can be used to adjust the parameters of the VLBI station seasonal displacement derived from the VLBI data only. The latter are estimated from the 24-h sessions observed with VLBI networks which include those antennas that also participate in the UT1 Intensives observing programs. Unfortunately, during the last years, such 24-h sessions are usually observed 3–10 times per month (depending on station), and the precision of the daily VLBI position estimates is significantly worse than the weekly averaged GPS position estimates (see results presented in Sect. 2). So, it would be tempting to use the GPS data to improve the VLBI station position variations.

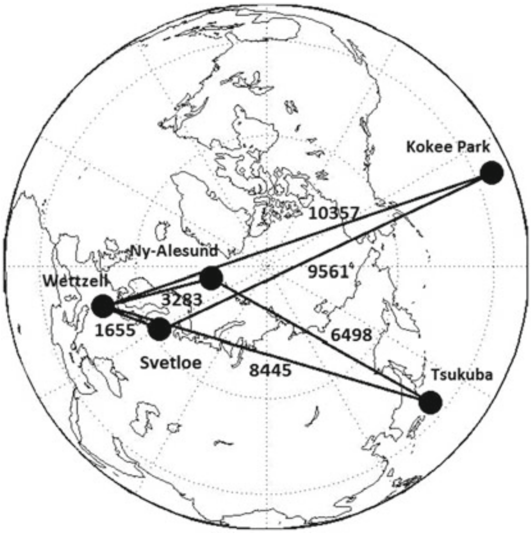

Fig. 1 Stations and baselines participating in the analyzed observing programs. The numbers are the baseline length in km

Then the impact of the seasonal VLBI station position variations on UT1 Intensives estimates is investigated. Previously, Schnell (2006) found from theoretical considerations and simulation that their impact on UT1 Intensives results should be small. In that study, the author assumed that the station position error is <2 mm. However, she neglected the seasonal signal in the station displacement, which can be several times larger. The goal of this work is to specify and quantify this effect on the basis of real Intensives data processing.

2 Seasonal station movements

In accordance with the goal of this study, the 5 VLBI stations most actively participating in the current IVS UT1 Intensives observing programs were considered. The station location and the network baselines are shown in Fig. 1. We also used GPS data from 8 collocated GPS stations having good observational history to investigate if it could be useful to improve the seasonal displacement model of the VLBI stations.

Finally, we used 13 stations located at five sites: Kokee Park (Hawaii, USA), Ny-Ålesund (Spitsbergen, Norway), Svetloe (Russia), Tsukuba (Japan), and Wettzell (Germany). All 13 stations are included in the ITRF2008 (Altamimi et al. 2011).

The data time interval was taken as 2004.0–2009.6. The latter data coincide with the end of the ITRF2008 data. The beginning of the interval is defined by the beginning of active observations by the Svetloe VLBI station.

For our analysis, we used the time series of the VLBI and GPS residuals computed from the ITRF2008 solution.[1] It should be mentioned that the authors warned that these series do not reflect the total station non-linear motions due

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[1] http://itrf.ensg.ign.fr/ITRF_solutions/2008/ITRF2008_ts.php.

Table 1 Station displacement time series and basic statistics: number of data points used in analysis (N), minimum and maximum interval between data points (Δ), year, and 3D weighted Allan deviation (WMADEV), mm

Station	Technique	N	Δ	WMADEV
Kokee park				
KOKEE (Kk)	VLBI	493	0.002–0.153	11.7
KOKB	GPS	287	0.016–0.038	2.4
Ny-Ålesund				
NYALES20 (Ny)	VLBI	345	0.002–0.115	6.8
NYAL	GPS	286	0.016–0.036	2.5
NYA1	GPS	287	0.013–0.028	2.4
Svetloe				
SVETLOE (Sv)	VLBI	258	0.002–0.115	10.8
SVTL	GPS	240	0.013–0.028	3.0
Tsukuba				
TSUKUB32 (Ts)	VLBI	251	0.002–0.153	7.6
TSKB	GPS	286	0.016–0.038	2.0
Wettzell				
WETTZELL (Wz)	VLBI	631	0.002–0.069	7.0
WTZA	GPS	283	0.017–0.095	1.9
WTZR	GPS	286	0.016–0.036	2.1
WTZZ	GPS	288	0.008–0.031	2.1

to adjustment of the translation, rotation and scale parameters during ITRF computation, see Collilieux et al. (2007) for details. However, our comparison of the ITRF residuals for IGS stations with the station position time series provided by the Jet Propulsion Laboratory[2] and the Scripps Orbit and Permanent Array Center[3] IGS Analysis Centers have shown that the agreement of the series is good enough for the purpose of the present study. On the other hand, using the ITRF2008 residuals has a large advantage over other series because it directly corresponds to the seasonal discrepancy in station position one introduces using the ITRF2008 model in space geodesy applications.

The selected station list along with basic statistics of the corresponding ITRF residual series is presented in Table 1. In the table, N is the number of data points of the original series falling in the given interval of dates, and WMADEV is the weighted modified three-dimensional Allan deviation as defined by Malkin (2008).

$$\begin{aligned} WMADEV &= \sqrt{\frac{1}{2p}\sum_{i=1}^{n-1} p_i\, d_i^2}\,, \\ d_i &= |\mathbf{y}_i - \mathbf{y}_{i+1}|, \qquad (1) \\ p &= \sum_{i=1}^{n-1} p_i\,, \quad p_i = \left(\sum_{j=1}^{k}\left[(s_i^j)^2 + (s_{i+1}^j)^2\right]\right)^{-1}. \end{aligned}$$

where $\mathbf{y}_i$, $i = 1 \ldots n$ are the k-dimensional vectors of measurements with the associated uncertainties $\mathbf{s}_i$, $i = 1 \ldots n$, p_i are the weights, $|\ldots|$ denotes the Euclidean norm. In our case, $k = 3$, which corresponds to the 3D vector $(\mathrm{d}E, \mathrm{d}N, \mathrm{d}H)$ of the station displacement.

WMADEV is an integrated measure of the stochastic behavior of the station position, giving a simple but effective one-parameter estimate of the data noise. The main advantage of using the Allan variance to estimate the noise component in the station movement is that it practically does not depend on the low-frequency variations, e.g. seasonal, which the rms estimate substantially depends on. More details on using the Allan variance in geodesy and astronomy can be found in Malkin (2011a, 2013) and papers referred therein.

As follows from Table 1, VLBI data have, on average, 3.7 times larger scatter than GPS data (see also Fig. 2). This can be explained by two reasons. The VLBI series consists of 24-h session estimates, whereas GPS station positions are obtained from a weekly averaged data set. This gives a factor of $\sqrt{7} = 2.65$ in position uncertainty. The remaining factor 3.70/2.65 = 1.4 can be attributed to the somewhat worse VLBI data precision as compared with GPS, in particular, due to the much more GPS observations made daily at each station (about two order greater than for VLBI).

Two methods of analysis were used to investigate the seasonal signal in the time series. First, the power spectral density was computed for all the series. The results are depicted in Fig. 3. Then, the data were fitted to a model

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[2] http://sideshow.jpl.nasa.gov/mbh/series.html.

[3] ftp://sopac-ftp.ucsd.edu/pub/timeseries/measures/.

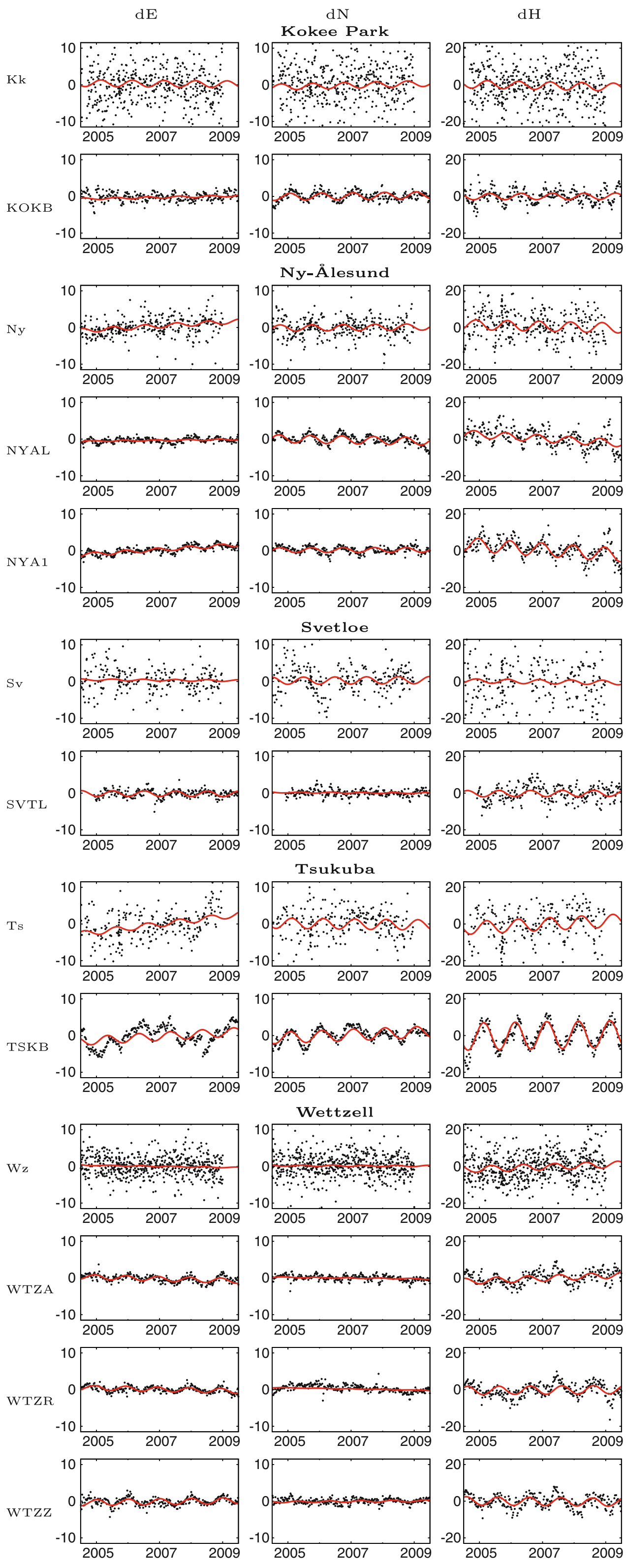

Fig. 2 ITRF residuals time series (*dots*) and the best-fit model comprising the linear trend and annual harmonics, *red line*). Note different scales for vertical ($\mathrm{d}H$) and horizontal ($\mathrm{d}E$, $\mathrm{d}N$) components. Unit: mm

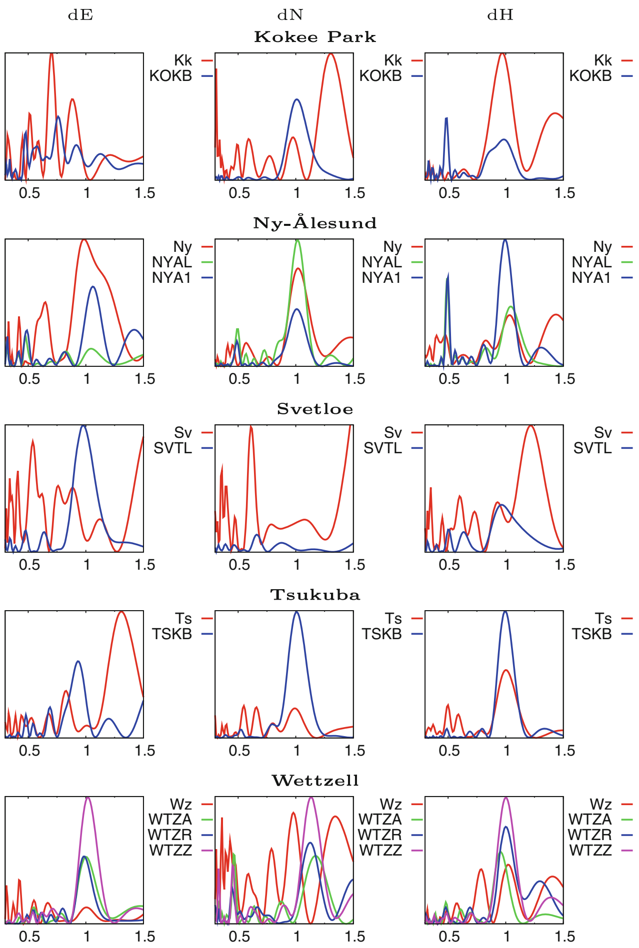

Fig. 3 Power spectra of the ITRF residuals time series grouped by sites, arbitrary units. Periods are in years

that comprises a linear trend, annual and semiannual harmonics, which corresponds to the widely used model for GPS station movements. The latter can also include, when appropriate, jumps in station position and an exponential term corresponding to post-quake relaxation. However, we do not need to consider these terms here because there were no earthquakes near the stations under investigation, and any episodic jumps are already included in the ITRF2008 model and, thus, are eliminated in the ITRF2008 residuals series. The parameters of the seasonal terms in the station position variations found in this analysis are given in Table 2.

Amplitude and phase analysis of the results presented in Table 2 along with spectral properties of the seasonal signals (Fig. 3) can help us to decide what part of the seasonal signal is related to the site, i.e. is caused by the local surface deformations, e.g. inaccurate modeling of the atmospheric or hydrology loading (Munekane et al. 2004; Petrov and Boy 2004; Munekane et al. 2010), and what part is station- or

Table 2 Estimated parameters of the seasonal harmonics in the ITRF residuals series: A_1, P_1 are the amplitude and phase of the annual term, A_2, P_2 are the amplitude and phase of the semiannual term. The phases are referred to epoch 2006.8 corresponding to the middle of the data interval. Units: mm, deg

Station	A/P	dE	dN	dH
Kokee park				
Kk	A_1	0.9 ± 0.2	0.8 ± 0.2	2.2 ± 0.5
	P_1	326 ± 15	96 ± 19	288 ± 15
	A_2	0.0 ± 0.2	0.3 ± 0.3	0.4 ± 0.5
	P_2	294 ± 269	67 ± 55	346 ± 81
KOKB	A_1	0.2 ± 0.1	0.9 ± 0.1	1.5 ± 0.3
	P_1	140 ± 30	354 ± 5	275 ± 10
	A_2	0.3 ± 0.1	0.3 ± 0.1	1.7 ± 0.3
	P_2	343 ± 24	91 ± 14	325 ± 9
Ny-Ålesund				
Ny	A_1	0.6 ± 0.1	0.9 ± 0.1	2.7 ± 0.5
	P_1	186 ± 12	107 ± 10	56 ± 10
	A_2	0.2 ± 0.1	0.1 ± 0.1	1.8 ± 0.5
	P_2	4 ± 39	210 ± 72	119 ± 15
NYAL	A_1	0.2 ± 0.1	1.0 ± 0.1	1.7 ± 0.3
	P_1	70 ± 20	121 ± 5	78 ± 11
	A_2	0.2 ± 0.1	0.7 ± 0.1	2.4 ± 0.3
	P_2	90 ± 14	230 ± 7	206 ± 8
NYA1	A_1	0.5 ± 0.1	0.6 ± 0.1	3.5 ± 0.3
	P_1	48 ± 7	106 ± 5	26 ± 4
	A_2	0.3 ± 0.1	0.5 ± 0.1	2.5 ± 0.3
	P_2	115 ± 10	255 ± 7	219 ± 6
Svetloe				
Sv	A_1	0.1 ± 0.3	1.0 ± 0.3	1.3 ± 0.9
	P_1	219 ± 105	200 ± 13	44 ± 37
	A_2	0.4 ± 0.3	0.1 ± 0.3	1.4 ± 0.9
	P_2	125 ± 37	338 ± 150	204 ± 38
SVTL	A_1	0.8 ± 0.1	0.2 ± 0.1	1.6 ± 0.4
	P_1	194 ± 5	243 ± 30	149 ± 12
	A_2	0.3 ± 0.1	0.2 ± 0.1	1.7 ± 0.4
	P_2	185 ± 14	78 ± 27	291 ± 12
Tsukuba				
Ts	A_1	0.8 ± 0.3	1.4 ± 0.3	5.1 ± 0.5
	P_1	155 ± 19	336 ± 11	318 ± 5
	A_2	0.1 ± 0.2	0.6 ± 0.3	3.3 ± 0.4
	P_2	5 ± 134	316 ± 27	348 ± 7
TSKB	A_1	1.1 ± 0.2	1.6 ± 0.1	7.4 ± 0.2
	P_1	255 ± 10	352 ± 3	328 ± 2
	A_2	0.5 ± 0.2	0.4 ± 0.1	1.7 ± 0.2
	P_2	336 ± 22	24 ± 15	108 ± 7
Wettzell				
Wz	A_1	0.1 ± 0.1	0.2 ± 0.1	1.8 ± 0.3
	P_1	221 ± 53	223 ± 37	240 ± 11
	A_2	0.1 ± 0.1	0.1 ± 0.1	0.7 ± 0.3
	P_2	53 ± 78	145 ± 82	18 ± 31
WTZA	A_1	0.7 ± 0.1	0.1 ± 0.1	1.6 ± 0.3
	P_1	38 ± 5	62 ± 31	185 ± 8
	A_2	0.0 ± 0.1	0.1 ± 0.1	0.9 ± 0.2
	P_2	32 ± 74	96 ± 27	325 ± 15
WTZR	A_1	0.6 ± 0.1	0.1 ± 0.1	2.3 ± 0.3
	P_1	42 ± 5	37 ± 51	154 ± 6
	A_2	0.1 ± 0.1	0.1 ± 0.1	0.5 ± 0.3
	P_2	194 ± 31	27 ± 31	332 ± 26
WTZZ	A_1	0.8 ± 0.1	0.3 ± 0.1	2.2 ± 0.2
	P_1	14 ± 4	265 ± 12	166 ± 6
	A_2	0.1 ± 0.1	0.1 ± 0.1	0.8 ± 0.2
	P_2	336 ± 38	208 ± 40	354 ± 16

technique-specific, i.e. is explained by unstable foundation, instrumental effects, or data analysis deficiencies, see, e.g., Dong et al. (2002). Detailed analysis of this problem is beyond the scope of this study. It is mostly important for us to make a decision on whether the parameters of the seasonal signal found in the GPS station displacement time series can help to improve the model of seasonal variations in the VLBI station positions.

One can see that the semiannual signal in the horizontal components of the station displacements is small, mostly well below 1 mm, and unstable. Analysis of the phases of the semiannual signal (see Table 2) shows that they are mostly different for the VLBI and GPS stations belonging to the same site. As to VLBI stations, Ts shows the greatest semiannual dN component with the amplitude of 0.6 mm. As to the height variations, the semiannual signal is more substantial at several stations: Ny, Sv, Ts, KOKB, NYAL, NYA1, and SVTL.

So, in this paper we concentrate on the investigation of the annual signal in station displacements. A statistically significant annual signal is present in most series. All the annual harmonics found for all the 13 stations are depicted in Fig. 4 grouped by sites. The largest dH amplitude is observed at Tsukuba stations Ts and TSKB—a well known fact from previous studies, see, e.g., Munekane et al. (2004). One can see that at all the sites, the annual signals for the stations belonging to the site differ substantially in amplitude and/or phase in at least one component. Table 2 gives more detailed information about the differences between the parameters of the annual signals found for collocated GPS and VLBI stations noticed in Fig. 4 by visual inspection. This results agree well with Tesmer et al. (2009) and Ding et al. (2005). However, the phase of the annual term in the height variations for Kk and Ny (the only common stations between this study and Ding et al. (2005)) found in our analysis agree much better than found in Ding et al. (2005).

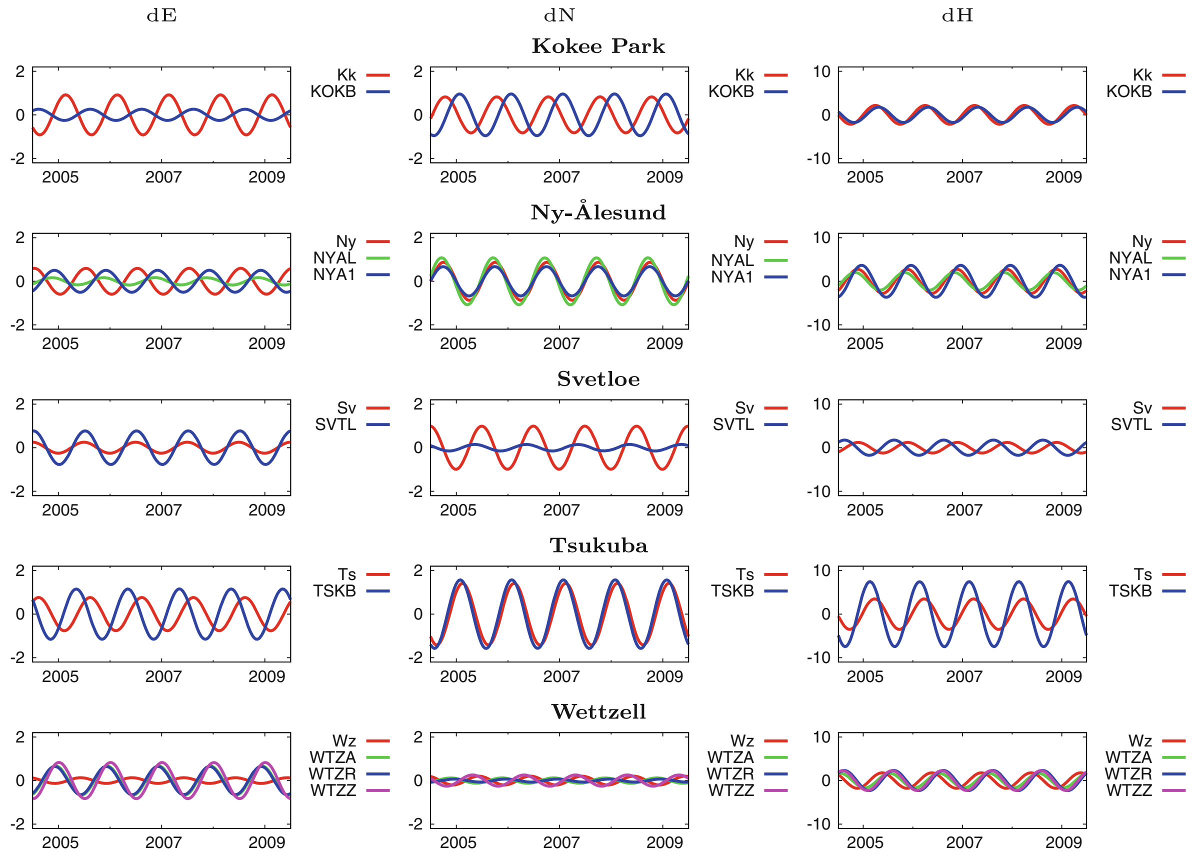

Fig. 4 Annual signal in the station displacement time series. Note different scales for vertical (dH) and horizontal (dE, dN) components. Unit: mm

Finally, we can make two main conclusions from the results of this section:

- Using the seasonal signal parameters found in the GPS stations position time series for refinement of the model of seasonal variations of VLBI station positions generally cannot be justified without additional investigation of the structure and nature of seasonal displacements.
- An annual harmonic model is a simple, but still sufficiently good approach for our study.

3 VLBI data analysis

Assessment of the impact of seasonal station position variations on UT1 Intensives results was made by processing VLBI data collected from the main Intensives programs for a 6-year interval from the beginning of March 2005 till the end of February 2011. The end of the interval is defined by the strong earthquake in Japan on March 11, 2011, which resulted, in particular, in a large displacement of the TSUKUB32, one of the key stations for the Int2 and Int3 IVS Intensives observing programs. This event was not accounted for in the ITRF2008 because it happened after its completion. Any current extension of the ITRF TSUKUB32 displacement model might be inconsistent with ITRF2008, and thus, is inappropriate for our study. The 10 days in March 2011 immediately preceding the March 11 earthquake were not included in the processing to avoid the possible impact of pre-quake earth surface deformations.

The list of observing programs used in this work along with basic statistics is given in Table 3. All the data available in this period were used except one Int1 session, 09SEP03XU, and one Int2 session, 09AUG29XK, each having five observations. Notice, that there was a gap in the series in 2010 caused by the Wettzell antenna repairs in the period from the beginning of September to the end of November.

The observations were processed in two solution modes: modeling station motion according to the ITRF2008 linear model and with addition of only the annual variations in the station displacement with the amplitude and phase found in the previous section for the VLBI stations. Substantial options used during the data processing were the following:

Table 3 Intensives UT1 series used in this study: σ_1 is the mean uncertainty, σ_2 is the median uncertainty, σ_3 is the WRMS difference with the IERS C04 series. Unit: µs

Series	Baselines	Start	End	Sessions	σ_1	σ_2	σ_3
Int1	KkWz	01-Mar-2005	28-Feb-2011	1,171	11.9	10.6	18.0
Int1a	KkSvWz	12-Mar-2005	13-Jan-2011	86	10.3	8.8	18.9
Int2	TsWz	05-Mar-2005	27-Feb-2011	530	8.8	8.2	9.9
Int3	NyTsWz	27-Aug-2007	28-Feb-2011	109	8.5	7.7	18.5

- Polar motion: IERS C04.[4]
- Celestial pole offset: ZM2 model[5] (Malkin 2007, 2011b).
- Source positions: ICRF2 (Ma et al. 2009).
- Atmospheric loading: the series provided by the GSFC Analysis Center.[6]
- Antenna thermal deformation model: Nothnagel (2009).

Consequently, four pairs of time series were obtained for four IVS UT1 observing programs described above. The results of these computations and comparison of UT1 estimates are shown in Fig. 5. The gap in the series in 2010 is caused by the Wettzell antenna repairs in the period from the beginning of September to the end of November. The errors σ_1, σ_2, and σ_3 given in Table 3 are the same for both solution modes.

The results of this test presented in Fig. 5 show that the strong annual signal is present in all the UT1 series, but with different amplitude: just over 1 µs for Int1 and Int1a series and 2–3 times smaller for Int2 and Int3 ones. The uncertainty of the amplitude estimates is much smaller than the amplitude itself. The annual spectral peak for Int3 is shifted slightly with respect to the nominal period of 1 year, but there are too few observations for this observing program to allow us to get a reliable spectrum. The amplitude of the semiannual term is below 0.15 µs for all the series.

The Int2 and Int3 differences also show a large signal at the period of 90 and 60 days, which can be a result of the periodicity in schedules (Hefty and Gontier 1997; Titov 2000). The amplitudes of the 90-day term in the Int2 and Int3 differences are 0.28 and 0.36 µs, respectively. The amplitudes of the 60-day term in the Int2 and Int3 differences are 0.31 and 0.33 µs, respectively.

One can see that the annual signal in the Int1a (KkSvWz baselines) UT1 series is similar to the annual signal in the Int1 series (KkWz baseline). This is also the case for Int3 (NyTsWz baselines) and Int2 (TsWz baseline). This means that the addition of a third station to the Int1 and Int2 networks does not significantly change the impact of the annual signal in the station displacement on UT1 estimates. A similar conclusion was made in Malkin (2011b) with respect to the impact of celestial pole modeling on UT1 Intensives results. Unfortunately, the small number of Int1a and Int3 sessions does not allow us to make a more detailed reliable analysis.

On the one hand, the precision and accuracy of UT1 Intensives results are improving as the baseline length grows. On the other hand, for a baseline of the length compared with the Earth's diameter, the two stations have a limited common visibility, which leads to poor and asymmetric sky coverage, which affects the UT1 Intensives results (Baver et al. 2004; Baver and Gipson 2010). Our analysis of the Int1 and Int2 schedules showed that the sky coverage for the Int1 sessions is more asymmetric as compared with the Int2 schedules. Such a large asymmetry in the sky coverage for Int1 sessions can be a main reason for the larger impact of the non-linear station movement on UT1 results.

4 Conclusions

In this paper, we investigated the impact of the seasonal station position variations on UT1 estimates obtained from the processing of VLBI Intensives observations.

At the first stage, we detected and investigated the seasonal signal in the 5 VLBI station displacement time series, along with position time series of 8 collocated GPS stations. The time series of the ITRF2008 residuals computed in the framework of computation of the ITRF2008 solution were used for this analysis. The differences were fitted to the model consisting of the linear trend and annual and semiannual harmonics. It was found that the amplitude of the seasonal term can reach 8 mm in the height component and 2 mm in the horizontal components. The semiannual harmonics is relatively small and unstable, and for most stations no prevailing semiannual signal was found in the corresponding frequency band. So, only the annual term was used for further detailed analysis. Comparison of annual signals found in the displacements of the collocated VLBI and GPS stations has shown that for some sites they differ substantially in amplitude and phase.

Further, it has been shown that the seasonal variations in the station movements cause systematic errors in UT1

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[4] ftp://hpiers.obspm.fr/iers/eop/eopc04/.

[5] http://www.gao.spb.ru/english/as/persac/fcn2.dat.

[6] http://lacerta.gsfc.nasa.gov/aplo_eph/.

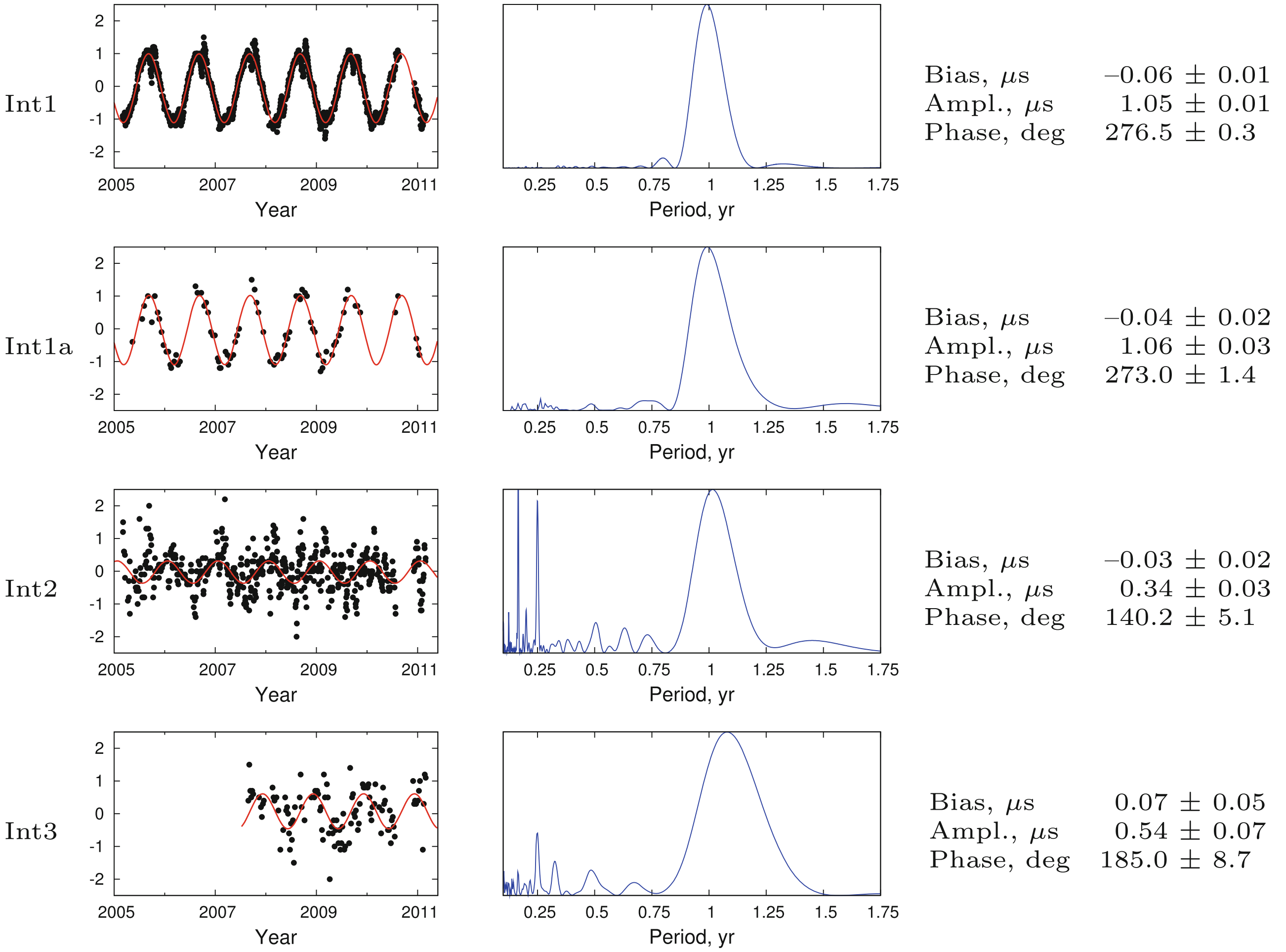

Fig. 5 Differences between two series of UT1 estimates computed with and without including the annual term in station position modeling. Data for four observing programs are shown from *top* to *bottom*: Int1 (baseline KkWz), Int1a (baselines KkSvWz), Int2 (baseline TsWz), Int3 (baselines NyTsWz). The *red line* corresponds to the model (bias and annual harmonics) fitted to the data. The *middle column* contains power spectra of the differences in arbitrary units. The best-fit model parameters (bias, amplitude and phase of the harmonics) are given in the *right column*. Unit: µs

results obtained from the processing of the VLBI Intensives observations. This error depends on the observing program design and schedule and exceeds 1 µs for the longest currently active IVS Intensives program Int1 (baseline KOKEE–WETTZELL). This value may seem insignificant, for it is below the current precision and accuracy of UT1 Intensives results (see Table 3). However, taking its systematic (seasonal) behavior into account, it should be considered substantial when using Intensives results for densification of UT1 series obtained from the multibaseline 24-h VLBI UT1 series with the accuracy at the level of a few microseconds (Gambis and Luzum 2011). Also, it becomes more substantial with coming improvements in the VLBI technique in the framework of the IVS VLBI2010 project (Petrachenko et al. 2009).

In our opinion, the results of this study give more weight to including a seasonal term(s) (as well as the post-quake exponential relaxation not considered in this paper) in the ITRF station position model as suggested, e.g., by Hugentobler et al. (2010), Malkin (2010b), Malkin et al. (2012), Altamimi et al. (2012), as is routine in some analysis centers for GPS station position modeling (Nikolaidis 2002). In this connection, it is very important to understand how it should be done. Generally speaking, two main options can be considered: define a non-linear motion model for the whole site (analogously to velocities) or use a specific model for each stations. It seems, that obtained results have clearly shown that the second option should be used to achieve a millimeter level accuracy of the stations motion modeling.

It should be emphasized that such an extension of the standard linear trend ITRF model is important not only for the current and future operational processing of the UT1 Intensives observations. The many year UT1 Intensives series is important for densification of the UT1 series obtained from the 24-h VLBI sessions. Reprocessing all the historical data collected, in the first place, on the intercontinental baselines, indeed after investigation of the seasonal variations of the stations involved, may be of importance for investigation of the Earth's rotation.

Finally, the method of analysis used in this work can be useful for the refinement of a scheduling strategy with respect to mitigation of the impact of the station non-linear motions on UT1 Intensives results, as well as on other parameters determined from the VLBI observations.

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