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Mechanism of error propagation from the subdaily Universal Time model into the celestial pole offsets estimated by VLBI

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Abstract

Within the analysis of space geodetic observations, errors of the applied subdaily Earth rotation model can induce systematic effects in different estimated parameters. In this paper, we focus on the impact of the subdaily Universal Time (UT1) model on the celestial pole offsets (CPO) estimated from very long baseline interferometry (VLBI) observations. We provide a mechanism that describes the error propagation from the subdaily UT1 into the daily CPO.

In typical 24-h VLBI sessions the observed quasars are well distributed over the sky. But the observations, if looked at from the Earth-fixed frame, are not homogeneously distributed. The amount of observations performed in different terrestrial directions shows an irregularity which can be roughly compared to the case where the observations are collected in only one Earth-fixed direction. This peculiarity leads to artefacts in VLBI solutions, producing a correlation between the subdaily variations in UT1 and the position of the celestial pole. As a result errors in diurnal terms of the subdaily UT1 model are partly compensated by the estimated CPO. We compute for each 24-h VLBI session from 1990 until 2011 the theoretical response of the CPO to an error in the subdaily UT1 by setting up a least-squares adjustment model and using as input the coordinates of the observed quasars and observation epochs. Then real observed response of the estimated CPO derived from the VLBI session solutions is compared to the predicted one. A very good agreement between the CPO values estimated from VLBI and the predicted values was achieved. The presented model of error propagation from the subdaily UT1 into the daily CPO allows to predict and explain the behaviour of CPO estimates of VLBI solutions computed with different subdaily Earth rotation models, what can be helpful for testing the accuracy of different subdaily tidal models.

Keywords: Earth rotation; Universal Time; Subdaily tidal models

1. Introduction

The orientation of the Earth in space is defined by the orientation of its axis and by the rotation angle of the Earth relative to some inertial reference system. The quasi-stellar radiosources (quasars), the farthest observed objects in the universe, are currently used to represent the inertial space, which is realized by the quasar coordinates (International Celestial Reference Frame (ICRF), Ma et al., 1998; Fey et al., 2015). The position of the Earth's axis in space is given by a precession-nutation model which describes the motion of the Earth's axis around the pole of ecliptic. As a measure for the rotation of the Earth around its axis the Universal Time (UT1) is used, which locates the Greenwich meridian in the inertial space. Since neither the orientation of the Earth's axis nor the position of the Greenwich meridian can be theoretically predicted with

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sufficient accuracy, the monitoring of the Earth rotation is needed in order to estimate small empirical corrections to the a priori theoretical values from space geodetic observations.

There are two definitions for these empirical corrections: the classical one and the new one (Seidelmann and Kovalevsky, 2002). In the classical definition the corrections to the nutation angles in longitude and obliquity ($\delta\psi, \delta\epsilon$) refer to the instantaneous vernal equinox. UT1 is defined through a connection to the Greenwich true sidereal time (Greenwich apparent stellar time GAST), and this connection contains nutation. Thus, it is impossible to fully separate the nutation from the irregularities in the Earth rotation speed. The new definition introduced by the International Astronomical Union (IAU, see e.g. Rickman, 2000) uses the concept of non-rotating origins (NRO) (Capitaine et al., 1986; Guinot, 1979): the celestial NRO replaced the vernal equinox and the terrestrial NRO replaced the Greenwich meridian. The angle between the celestial and the terrestrial NRO measured along the equator is called the Earth Rotation Angle (ERA). UT1 is directly proportional to the ERA. The non-rotating origins are defined in such a way that if the celestial equator changes slightly its position due to a change in nutation, the respective changes in the position of both the celestial and terrestrial NRO do not have any component along the equator. Thus, in the new formulation the nutation is fully decorrelated from UT1. The new nutation corrections are called Celestial Pole Offsets (CPO dX/dY).

Very long baseline interferometry (VLBI) is the only technique of space geodesy which can directly measure the absolute orientation of the Earth in space by observing the quasars. The observations from the ground-based network of stations are organized and coordinated by the International VLBI Service for Geodesy and Astrometry (IVS, Nothnagel et al., 2016). The observations are usually collected within 24-h observing sessions and there are several sessions per week available. The routine estimation of the five Earth Orientation Parameters (EOP, including the polar motion, UT1 and the nutation corrections) is one of the main products of the IVS. The nutation corrections are estimated from each available 24-h session. The UT1 is additionally estimated from special daily 1-h intensive sessions (IVS-INT). A clear understanding of the effects influencing the nutation corrections and the UT1 values in the VLBI analysis is important, since the nutation corrections cannot be compared to any results obtained by other observation techniques. Thus, eventual systematic influences on the estimated nutation parameters have to be carefully investigated.

The subdaily variations in the Earth rotation are mostly caused by the ocean tides, they can reach values significant for the current accuracy of the solutions and thus have to be taken into account in the processing of geodetic observations. For this reason the a priori values for polar motion and UT1 must contain the theoretically computed subdaily variations. There is a standard subdaily model derived from an ocean tide model (see Egbert et al., 1994; Ray et al., 1997) which is recommended by the International Earth Rotation and Reference Systems Service (IERS) for routine use in the processing. It provides the amplitudes of variations in the Earth rotation parameters (ERP) for a set of tidal periods. The current IERS subdaily model contains 41 tidal terms with daily and 30 tidal terms with semi-daily periods and can be found in the current IERS Conventions (Petit and Luzum, 2010). The accuracy of the IERS subdaily model is on one hand limited by the accuracy of the underlying ocean model, on the other hand it does not contain any variations in the Earth rotation caused by other phenomena than the ocean tides. The latter fact leads to noticeable deviations of the real observed variations from the model for some tidal waves. For example, for the period of 24.00 h (tide S1) there is nearly zero variation given by the IERS model, since the gravitational tidal potential for this period is close to zero. But there is a radiational tide of this period due to the solar heating cycle, which causes a noticeable variation in the Earth rotation. The realistic accuracy of the IERS model can be estimated by comparing it to different empirical tidal models computed from geodetic observations. The accuracy is estimated by, e.g., Griffiths and Ray (2013) to about 20%. This poses a question about the possible systematic influences of the errors in this model on other estimated parameters.

In our previous study (Panafidina et al., 2017) the impact of errors in the a priori subdaily polar motion on the estimated CPO was considered. It was shown that spectral inseparability between different subdaily signals leads to a mistaking of a part of the signal in polar motion for a retrograde daily wave which represents the nutation. This effect, present in any 24-h solution, is leading to systematic errors in the estimated nutation offsets. As a continuation, the current paper investigates the impact of the a priori model for subdaily variations in the speed of Earth rotation. As we found, the estimated CPO are influenced in a systematic way in this case as well, but the reasons and the mechanism of this influence are different from the case of the subdaily polar motion.

It has to be emphasized here that in the present study the new parameters (CPO dX/dY) for the nutation corrections were used, what means that there is no intrinsic dependency between the estimated CPO and UT1. Thus, the found correlation between them cannot be explained by this dependency and we do not consider or mention this possibility further. Under "correlation" we mean not the mathematical correlation between the parameters present in the normal equation matrix, but a systematic and predictable effect of subdaily variations in UT1 on the nutation parameters. For the case of classical nutation corrections ($\delta\psi, \delta\epsilon$) our investigations (not presented here) showed that the existence of the intrinsic dependency between the parameters cannot influence the discussed correlation between them. Therefore, the main conclusion of the current study hold also for the classical definition of the nutation corrections and UT1.

The principle of the connection between the nutation and UT1 is discussed in Section 2. Section 3 mentions shortly the main features of the solutions. The estimated CPO from VLBI solutions and the theoretical response of nutation offsets to a change in the subdaily UT1 are discussed in Section 4. Section 5 shows an example of the influence of an empirical UT1 model on the estimated CPO. Finally, in Section 6 for completeness the influence of the subdaily variations in the speed of Earth rotation on the daily ERP is discussed.

2. Nutation offsets and the Universal Time

To explain how the nutation and the Earth rotation angle are connected we consider a quasar Q with catalogue coordinates $(\alpha,\delta)_{[CRF]}(t_0)$. These are coordinates in the CRF referring to the celestial equator and the equinox of the standard epoch t_0 of the used catalogue (e.g. J2000). To compute the a priori direction $(\alpha,\delta)_{[TRF]}(t)$ to this quasar in the terrestrial frame at the epoch of observation t, the expression for the transformation between the CRF and TRF can be used (see e.g. IERS Conventions):

$$[Q_{TRF}](t) = PM(t)\cdot ERA(t)\cdot PN(\Delta t)[Q_{CRF}](t_0) \quad (1)$$

where:

$[Q_{TRF}](t)$ are quasar coordinates in the TRF at t
$[Q_{CRF}](t_0)$ are quasar coordinates in the CRF at t_0
Δt is the time interval between t_0 and t
PN is the precession-nutation matrix
ERA is the Earth rotation angle at epoch t
PM is the polar motion at epoch t

The reduction of the astronomical observations includes many other steps, but we consider only those steps which are relevant for our study. If all the a priori values were perfectly correct, we would observe the quasar right in the place which has been computed using (1). What happens if the precession-nutation matrix used in (1) is slightly changed? Then the quasar coordinates in the celestial intermediate system which are obtained by applying the $PN(\Delta t)$-rotation to the catalogue quasar position would also change. These changes in the quasar's coordinates sometimes can be partially or fully compensated within the transformation (1) by the ERA, i.e. by adjusting UT1 which is linearly dependent on the ERA. We assume here that the PN matrix in Eq. (1) remains essentially the same, as given by a precession-nutation model in use, and only additional small empirical CPO (dX,dY) are changing. If the applied nutation offsets are changed by small rotations $(\Delta X,\Delta Y)$ the resulting quasar coordinates would slightly change as well by $(\Delta\alpha,\Delta\delta)$. The changes in the right ascension $\Delta\alpha$ and in the declination $\Delta\delta$ are connected to the changes in CPO $(\Delta X,\Delta Y)$ through the following expressions:

$$\Delta\alpha = (\Delta X\cdot\sin\alpha + \Delta Y\cdot\cos\alpha)\tan\delta \quad (2)$$

$$\Delta\delta = \Delta X\cdot\cos\alpha - \Delta Y\cdot\sin\alpha \quad (3)$$

These expressions can be inferred from the linearized equation connecting the initial position of a quasar (α,δ) and its new position $(\alpha+\Delta\alpha,\delta+\Delta\delta)$ by two small rotations $(\Delta X,\Delta Y)$ around y- and x-axis.

The right ascension change $\Delta\alpha$ can be compensated by a change in UT1, since both $ERA(t)$ and the right ascension after applying the $PN(\Delta t)$-rotation are measured along the same celestial equator. Thus, in Eq. (2) we can put $\Delta\alpha = -\Delta UT1$ to compute the change in UT1 which will compensate the right ascension change caused by a known change in CPO. The declination change $\Delta\delta$ cannot be compensated by UT1. We can see special cases in Eq. (2): for a quasar at pole $(\delta = 90)$, which has no defined right ascension, Eq. (2) is singular. And for a quasar at the equator $(\delta = 0)$ the change in the CPO cannot be even partially compensated by UT1, since there is no change in the right ascension.

Considering the opposite question whether a change in UT1 can be corrected for by adjusting the CPO values, we may notice that this can always be done for any quasar which does not lie on the equator or at the pole. We can use Eq. (2) and (3) with the condition $\Delta\delta = 0$ ($\Delta\delta$ must be zero, since a change in UT1 leads to a change in the right ascension, but leaves the declination unaffected) to find the respective changes in the CPO $(\Delta X,\Delta Y)$ which will fully compensate a known change in UT1 $(=\Delta\alpha)$:

$$\Delta X = \frac{\Delta\alpha\cdot\sin\alpha}{\tan\delta} \quad (4)$$

$$\Delta Y = \frac{\Delta\alpha\cdot\cos\alpha}{\tan\delta} \quad (5)$$

Summarizing, if only one quasar (with any declination except 0° and 90°) at one epoch is considered a small change in UT1 can always be fully compensated by a change in CPO, and a small change in CPO can be at least partially compensated by adjusting UT1, as shown by Eqs. (2)–(5). If many quasars and many observation epochs are processed together, as it is the case in real processing, the above conclusions in general do not hold. From Eq. (2) it is clear that $\Delta\alpha$ associated with known $(\Delta X,\Delta Y)$ will be different for different quasars. For example, for two quasars with either the same right ascensions and opposite declinations or the same declinations and opposite right ascensions the computed $\Delta\alpha$ is the same in size, but opposite in sign. Thus, finding a value for $\Delta\alpha$ which would fit all the observed quasars should lead to cancelling the effect if the distribution of observations is homogeneous. Similarly, if we want to find one set of CPO values which will compensate a known change in UT1 for many quasars, the effect should be cancelled. But it will not fully cancel if there is some asymmetry in the distribution of observations. We will now consider a special case of asymmetrical distribution which has a practical significance for VLBI sessions.

Let's imagine that during a 24-h session we use only one baseline and the orientation of participating telescopes is fixed in the terrestrial frame. Let's denote the celestial direction in which the telescopes are looking at the beginning of the session (α, δ). Then due to the daily rotation of the Earth the right ascension of the observed point on the sky would be changing as $(\alpha + \omega \cdot \Delta t)$, where ω is the speed of Earth rotation and Δt is the time passed from the beginning of the session. In the terrestrial frame the direction would remain the same throughout the session, since the telescopes do not change their orientation. For this imaginary case we can re-write Eq. (2) to compute the change in the right ascension associated with a change in CPO for any epoch t within the session:

$$\Delta\alpha(t) = (\Delta X \cdot \sin(\alpha + \omega t) + \Delta Y \cdot \cos(\alpha + \omega t)) \tan \delta \qquad (6)$$

It turns out that $\Delta\alpha(t)$ is a harmonic function with the frequency ω, which corresponds to a period of one sidereal day. Eq. (6) demonstrates that in the described imaginary case a small change in the CPO would lead to a wave with a period of one sidereal day in the right ascension. If the quasar coordinates are kept fixed, this wave will appear in UT1 estimates. To see this wave we would need to compute two 24-h VLBI solutions with slightly different a priori nutation offsets, keep them fixed in the processing (together with the quasar coordinates) and estimate UT1 with a subdaily resolution (e.g. 1 h). In the differences between the estimated sub-daily UT1 the diurnal wave will be well seen.

In real sessions VLBI observations are performed in all directions, so the above case should not be valid. But it can be relevant in some mean sense, if the quasar observation directions in the Earth-fixed frame are inhomogeneously distributed. To make a quick check whether this situation appears for usual 24-h VLBI sessions we searched for the diurnal wave in estimated UT1 as predicted by Eq. (6). Two VLBI solutions were computed, with UT1 estimated hourly and the nutation fixed to the a priori model. In the first solution the CPO corrections dX and dY were set to zero while in the second solutions these corrections were set to dX = 0.1 mas, dY = 0. The subdaily UT1 differences between these two solutions for the time span of the CONT02 campaign (from October 16 till October 31, 2002, Thomas et al., 2016) are shown in Fig. 1. The diurnal wave in the hourly estimated UT1 is well seen, the amplitude is about half of the nutation change (UT1 is plotted in mas).

The diurnal wave in UT1 in response to a change in CPO can be considered as a proof that there is a prevalent terrestrial direction in the VLBI observations, permitting the interference mechanism between subdaily UT1 and CPO described above. In some cases it is possible to see the asymmetry directly in the distribution of the observations. As an example we show session 00APR18XE on 18th of April, 2000. The distribution of the observed quasars over the sky for this session is shown in Fig. 2 and is rather homogeneous, though there is a clear positive shift in declinations. The picture changes if we look at the amount of the observations performed in different directions in the Earth-fixed frame. For this we take the list of observations and compute for each observation the terrestrial (geographical) longitude λ of the observed quasar - it is the longitude of its culmination at the observation epoch, which can be computed using the $ERA(t)$ at the observation time t and the right ascension α of the observed quasar:

$$\lambda = \alpha - ERA(t) \qquad (7)$$

Then, within the selected session we compute the number of observations of quasars at different terrestrial longitudes and latitudes (which for our purposes were considered equal to declinations). The result of this computation is shown in Fig. 3. The number of observations is accumulated in $10^\circ \times 10^\circ$ bins in longitude and declination. It can be seen that the majority of observations lies around longitudes 280°and latitudes 30°, thus approaching the hypothetic single-direction observation case used above to discuss the correlation mechanism between UT1 and CPO.

The systematic effect in VLBI solutions for different sessions may differ noticeably due to different observing networks and schedules. For the CONT campaigns the picture remains essentially the same for all days, because the observations during the campaigns are performed using the same station network and the same session set-up. This allows to see a continuous wave in UT1 shown in Fig. 1.

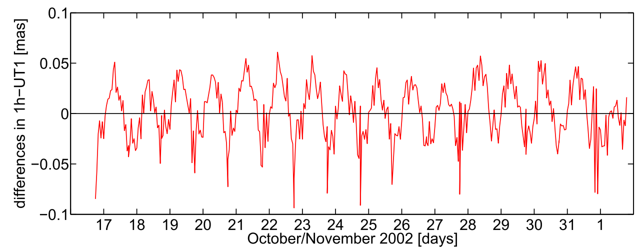

Fig. 1. Differences in estimated 1-h UT1 between VLBI solutions computed with fixed nutation: (1) CPO corrections are zero (dX = 0, dY = 0); (2) CPO corrections are changed (dX = 0.1 mas, dY = 0).

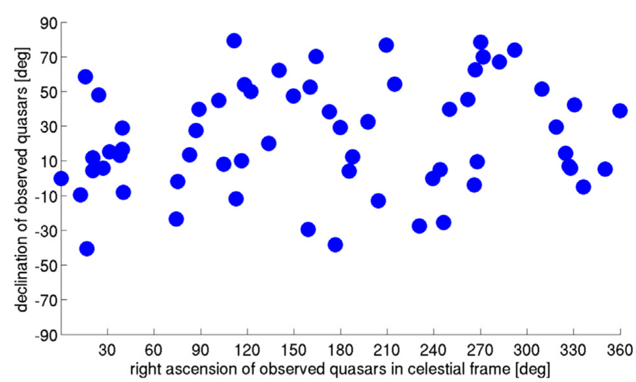

Fig. 2. Celestial coordinates of the observed quasars for session 00APR18XE.

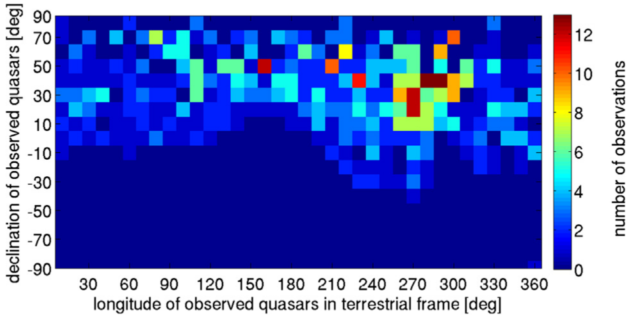

Fig. 3. Distribution of observation directions in Earth-fixed frame for session 00APR18XE.

We showed that there is a possibility for a 24-h VLBI session to absorb errors in the nutation offsets by adjusting subdaily UT1, or the other way around, to absorb errors in the diurnal wave in UT1 with a period of one sidereal day (K1 tide) by adjusting one set of CPO per session. Eq. (2) can be used as a model of error propagation. Since the regular 24-h session solutions are usually keeping the subdaily UT1 fixed to an a priori model and estimating the nutation offsets together with the polar motion and UT1 once per session, we focus further on the influence of possible errors in the subdaily tidal model of UT1 on the CPO estimated from VLBI observations. Further we describe the used VLBI data and computed solutions.

3. VLBI data and solutions

The analysis of the VLBI measurements was carried out with the software VieVS (Boehm et al., 2012) and it was identical to our previous study (Panafidina et al., 2017) where the full description can be found. The created normal equation systems (NEQ) of the single 24-h VLBI sessions between the years 1990 and 2011 served as basis for the further solutions and their modifications at the NEQ level. The considered data time span was predefined by the availability of the processed VLBI solutions at TU Vienna. The following session solutions were computed: polar motion and UT1 estimated as 24-hourly piece-wise-linear functions, CPO and the station coordinates estimated once per session. All manipulations of NEQ and computation of final solutions were done using the Bernese GPS Software (Dach et al., 2015).

The approach to change the subdaily model at the NEQ level is described in detail in Panafidina et al. (2014): the subdaily ERPs can be transformed into tidal terms (Artz et al., 2011), then their a priori values can be changed (Thaller, 2008). As a result, the CPO based on different subdaily ERP models can be estimated and compared.

4. Impact of errors in the subdaily UT1 model on the estimated CPO

The impact of the chosen a priori subdaily UT1 model can be made visible by comparing the CPO computed from VLBI solutions with different subdaily UT1 models. To see the systematic effect we consider a time series over the years 1990–2011 of differences in CPO between VLBI solutions computed with the IERS tidal model and with a model where one term in subdaily UT1 was changed by 10 μs.

The theoretical effect on nutation caused by a change in the subdaily UT1 can be computed as described in Section 2. The input VLBI data in the VieVS software are the so-called NGS-card files which contain basic information about each observation, such as, e.g., the names of the participating antennas, name of the observed quasar and time of the observation. Using this information we can write for each observation Eq. (2), where $\Delta\alpha$ is replaced by the $\Delta UT1(t)$, the intentional change in the subdaily UT1 at the time of the observation. Then the CPO fitting all the observations are computed using the least-squares (LS) method. Additionally, the linear trend in UT1 was estimated for each 24-h session, since UT1 is also estimated as a piece-wise-linear function in the VLBI solutions used for the comparisons.

This procedure is fully justified only for changes in the K1 term (with a period of one sidereal day), as discussed in Section 2. When another diurnal UT1 term is changed, we still can expect a consistent result, because over 24 h it is not possible to discriminate between the diurnal signals well enough. But for the semi-diurnal terms we can expect to see more or less no effect in the computed CPO.

In this LS-estimation the weighting of the individual observation equations plays an important role - it allows us to eliminate the singularity in Eq. (2) and to model realistically the contribution of the quasars depending on their declinations. Quasars lying close to the celestial poles (declinations close to $+90^\circ$ and close to -90°) are less affected by a change in the Earth rotation angle than quasars located close to the equator. They are less sensitive to UT1 and should contribute respectively less to the estimated nutation offsets than the quasars at low declinations. Also the relative geometry of the observing baseline and the direction to a quasar influences the sensitivity of an observation to UT1: if the change in the direction to a quasar due to Earth rotation is perpendicular to the baseline, the observation will be insensitive to UT1 and will not contribute to the estimated nutation offsets. Thus, we used as weights the difference between the VLBI observables (time delays between the arrivals of the wave front from a quasar at two radio telescopes) for the initial quasar position (α, δ) and the new quasar position $(\alpha + \Delta\alpha, \delta + \Delta\delta)$, i.e. the sensitivity of the measurement to the position change of the quasar due to nutation offsets. The weights are proportional to $\cos^2\delta$, what eliminates the singularity in the observational equations, as well as the strong dependency of the computed CPO on the declinations of the quasars.

This procedure was performed for each NGS-file with observations of a 24-h session which was used in the processing. The LS-estimated nutation response to a change in the subdaily UT1 was computed for different subdaily tidal terms. Each time one subdaily UT1 term was considered with 10 µs amplitude for sine and for cosine. The results were compared to the time series of differences in CPO obtained from VLBI solutions when the same UT1 tidal term was changed by 10 µs.

In Fig. 4 we demonstrate such a comparison for the case of changed S1 (24.00 h) tidal term in UT1. As can be seen the VLBI (red) and the LS-estimated (blue) nutation offsets are in a good agreement for both dX and dY. The main variation has a period of one year corresponding to the beat period between the sidereal day (23.93 h) and the S1 term. Both LS and VLBI time series are rather noisy, the amplitude of the yearly wave is varying, nearly disappearing to the end of the time series. The noise and the changes in the amplitude of the systematic signal are expected, since the effect on nutation is very changeable from session to session. On the other hand, the structure of the sessions is stable enough to see the effect in nutation over many years. The amplitude of the variation in nutation roughly corresponds to the changes applied to the S1 tidal term (10 µs equals to 150 µas). Vanishing of the systematic signal at the end of the time series signifies that the distribution of the observations within VLBI session became more homogeneous.

In Fig. 5 we demonstrate another example for the case of changed K1 (23.93 h) tidal term in UT1. This tidal term in UT1 leads to a constant shift in the estimated nutation offsets. This shift is present in both LS and VLBI time series, but at the same time some discrepancies between the VLBI and LS-solutions are obvious. The most noticeable feature is that the nutation differences from VLBI solutions demonstrate additionally to the constant shift a systematic variation with a period of about half an year. Since in Fig. 5 this behaviour is masked by the theoretical LS-values, we show in Fig. 6 a part of the time series of CPO dX differences from VLBI for the years 1990–1995, where the periodic wave is well seen. This effect can be explained by the following mechanism: the uncompensated systematic changes in the apriori subdaily UT1 lead not only directly to a change in nutation offsets, but also to a systematic change in the subdaily polar motion. The more detailed discussion of this effect is presented in Section 3 where the ERP are considered. This additional variation in polar motion influences in turn the nutation by a mechanism described in Panafidina et al. (2017): a part of the signal in polar motion is mistaken by the solution for the retrograde daily term which corresponds to nutation. This additionally affects the CPO in a systematic way. Thus, in case of UT1 the estimated CPO are influenced both directly by errors in the subdaily UT1 and indirectly by the induced errors in the subdaily polar motion. The indirect effect must be small and unstable, since the variations in polar motion depend strongly on the observing network which

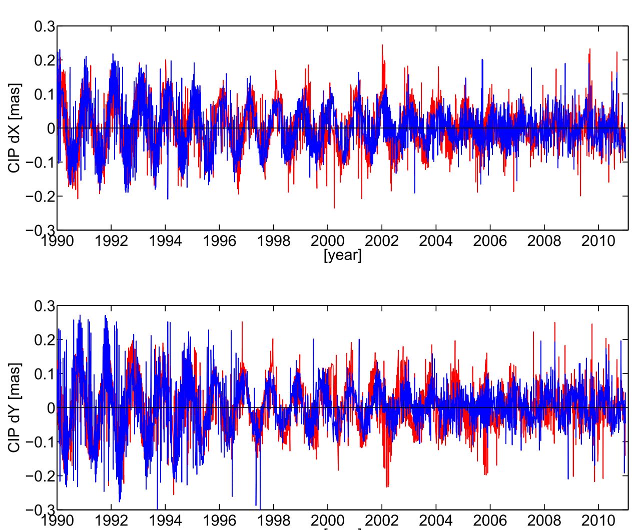

Fig. 4. Differences in estimated CPO (dX top, dY bottom) between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the S1 term (24.00 h) in UT1 was changed by 10 µs (red) vs. expected theoretical nutation offsets computed by least squares (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

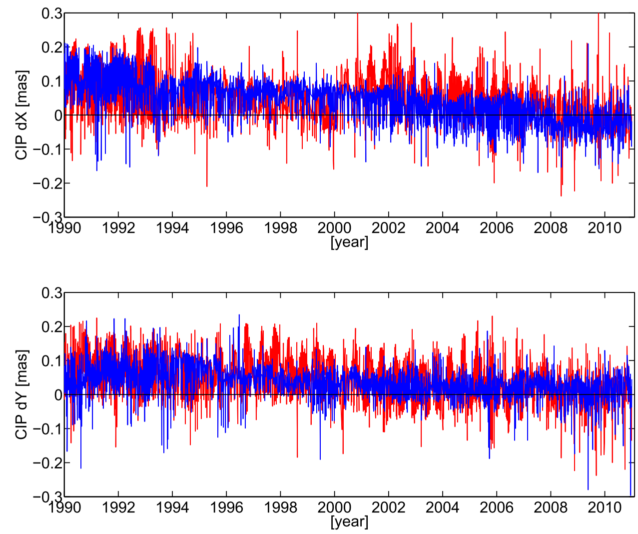

Fig. 5. Differences in estimated CPO (dX top, dY bottom) between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the K1 term (23.93 h) in UT1 was changed by 10 µs (red) vs. expected theoretical nutation offsets computed by least squares (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

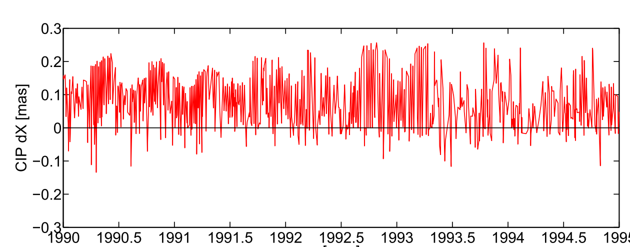

Fig. 6. Differences in estimated CPO dX between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the K1 term (23.93 h) in UT1 was changed by 10 µs for the time span 1990–1995.

changes from session to session. The prograde K1 (23.93 h) wave in the polar motion leads to a nutation change with a period of half an year (Panafidina et al., 2017), what seems to confirm the consideration above. The time series for the case of changed S1 (24 h) term in UT1 does not show noticeable discrepancies between the VLBI and the LS-solutions because in this case the indirect effect on nutation from the subdaily polar motion has the same period of one year as the direct effect from the changed UT1.

Since only the diurnal UT1 terms are connected to the CPO, UT1 tidal terms with semi-daily periods should leave the estimated nutation offsets unaffected. At the same time the indirect effect on nutation caused by the implicit change of the subdaily polar motion should still be there. As an example, we demonstrate in Fig. 7 a time series of CPO differences estimated from VLBI observations with the standard IERS subdaily model and a model where the semi-daily term K2 (11.97 h) in UT1 was changed by 10 μs. Some small systematic variations can be seen there.

The periods P of the variations in the CPO time series produced by a diurnal tidal wave in UT1 with period P_{tide} can be computed by:

$$P = \left(\frac{1}{P_{K_1}} - \frac{1}{P_{tide}}\right)^{-1} \qquad (8)$$

where P_{K_1} is one sidereal day.

The periods for 5 main diurnal tidal terms are listed in Table 1. For completeness we show in Figs. 8–10 the influence of the other three daily tidal waves in UT1 on the estimated nutation corrections. Since the behaviour of the time series is very similar for dX and dY CPO components, we show for these waves only the dX component. The time series for the case of changed O1 (25.82 h) tidal term in UT1 looks like a scatter for the whole time span 1990–2011, but

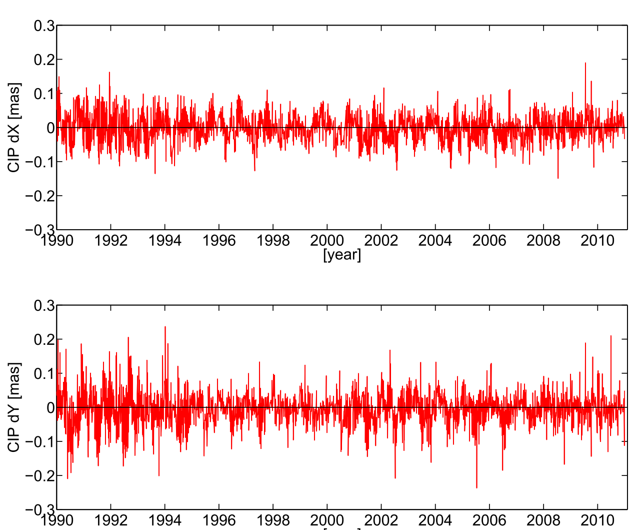

Fig. 7. Differences in estimated CPO (dX top, dY bottom) between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the K2 term (11.97 h) in UT1 was changed by 10 μs.

Table 1
Periods of variations in nutation time series caused by 5 main daily tidal terms in UT1.

Tide	Period [hours]	Period of variations in nutation [days]
Daily tidal terms		
Q1	26.87	9.13
O1	25.82	13.66
P1	24.07	182.61
S1	24.00	365.24
K1	23.93	∞

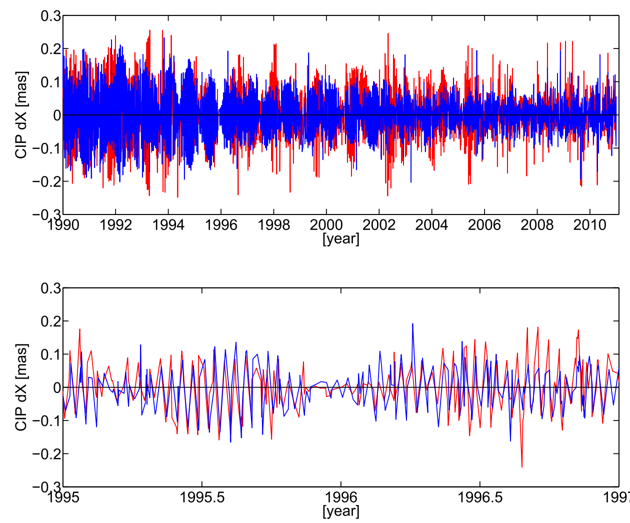

Fig. 8. Differences in estimated CPO dX between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the O1 term (25.82 h) in UT1 was changed by 10 μs (red) vs. expected theoretical nutation offsets computed by least squares (blue): time span 1990–2011 (upper plot) and time span 1995–1997 (lower plot). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

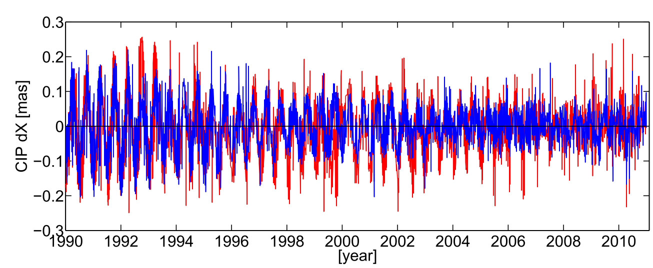

Fig. 9. Differences in estimated nutation offsets dX between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the P1 term (24.07 h) in UT1 was changed by 10 μs (red) vs. expected theoretical nutation offsets computed by least squares (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

when zoomed, it reveals a systematic variation with a period of about 14 days (Fig. 8).

The time series for the case of changed P1 (24.07 h) tidal term in UT1 (Fig. 9) shows the expected half-yearly variation. The time series for the case of changed Q1 (26.87 h) tidal term in UT1 (Fig. 10) is rather scattered. The period

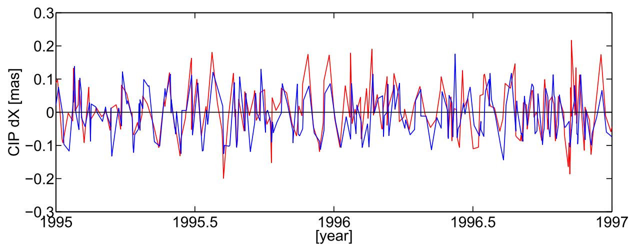

Fig. 10. Differences in estimated nutation offsets dX between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the Q1 term (26.87 h) in UT1 was changed by 10 μs (red) vs. expected theoretical nutation offsets computed by least squares (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in nutation offsets induced by this UT1 tide is about 9 days, what is probably too short for the VLBI solutions: there are not enough sessions (it can be only two or three) over such time spans to define the wave in nutation well.

It may be noted that the mathematical correlation between the CPO and UT1 seen in the NEQ is close to zero no matter with what temporal resolution UT1 is estimated. This allows to estimate these parameters together in one solution. If UT1 is estimated with a subdaiy resolution, all the errors of the a priori UT1 model will be absorbed and corrected for by the UT1 itself, leaving the rest of the solution unaffected, thus leaving the nutation estimates unbiased as well.

5. Impact of an empirical model for UT1 on the estimated CPO

To test a possible realistic effect of changing the underlying UT1 subdaily model on the CPO estimated by VLBI, we may use an empirical model for the subdaily variations in the Earth rotation. In the literature one can find empirical ERP models from e.g. GPS observations (Rothacher et al., 2001), from VLBI observations (Gipson, 1996; Artz et al., 2011) or from a combination of GPS and VLBI data (Artz et al., 2012). For our test solutions here we used the VLBI-only subdaily model published in Artz et al. (2011). The estimated amplitudes of several tidal terms in UT1 in this model show noticeable deviations from the amplitudes given by the standard IERS tidal model. The most affected UT1 terms with daily periods are the K1 (23.93 h), S1 (24.00 h), O1 (25.82 h) and OO1 (22.31 h). The deviations for each of these terms are at the level of 1 μs or more for the sine and/or cosine amplitude. The most deviating term is O1. The effect on nutation can be expected at the level of 15 μas. The term O1 will cause a variation in nutation estimates with periods of about 14 days (see Table 1). The term OO1 will cause a high-frequency variation in nutation with periods of about 14 days as well. This term is not shown in Table 1, since it does not count as one of the big terms, but the period caused by this term can be computed using Eq. (8).

Fig. 11 shows the respective time series of differences in CPO between the VLBI solutions computed using the IERS model and using a model where the UT1 variations were replaced by the empirical model from Artz et al. (2011). In both solutions the a priori polar motion included the standard IERS model. The constant shift seen in the beginning of dX time series of about 20 μas must be caused by changes in the K1 term amplitude. In Fig. 12 a part of the time series is shown for the years 1990–1993 and the variation which can be attributed to the influence of O1 term is well seen there.

The overall scatter is relatively large lying between 50 and 100 μas, what can also be relevant in practice (Bachmann et al., 2016).

6. Subdaily model for UT1 and the estimated daily ERP

As can be seen from Eq. (1) the errors in UT1 can be absorbed not only by the CPO, but also by the last rotation *PM*, the polar motion. For this reason the effect seen in the estimated daily polar motion is significant. Daily UT1 estimates are also noticeably affected by errors in the subdaily UT1 model. For completeness we discuss here shortly the respective results.

The UT1 daily estimates are absorbing the linear trend in the UT1 variations given by the used subdaily model. Thus, when a tidal term in the a priori subdaily UT1 is changed, the daily UT1 estimates change respectively. The rate (i.e. LOD) is much more affected than the offsets, what has been pointed out before (Kouba, 2003). We show the effect in Fig. 13, where the differences in the estimated offsets and rates in UT1 are presented for the VLBI solutions computed using the standard IERS tidal model and using a subdaily model where the K1 (23.93 h) wave in UT1 was changed by 10 μs. In our VLBI solutions the

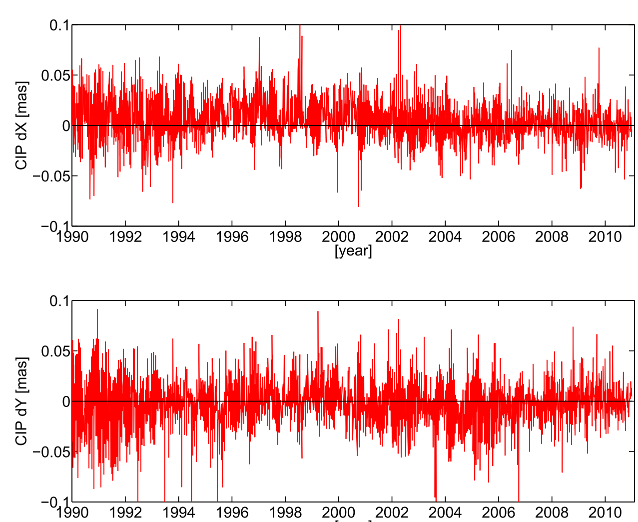

Fig. 11. Differences in estimated CPO (dX top, dY bottom) between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where UT1 variation are from the VLBI empirical model published in Artz et al. (2011).

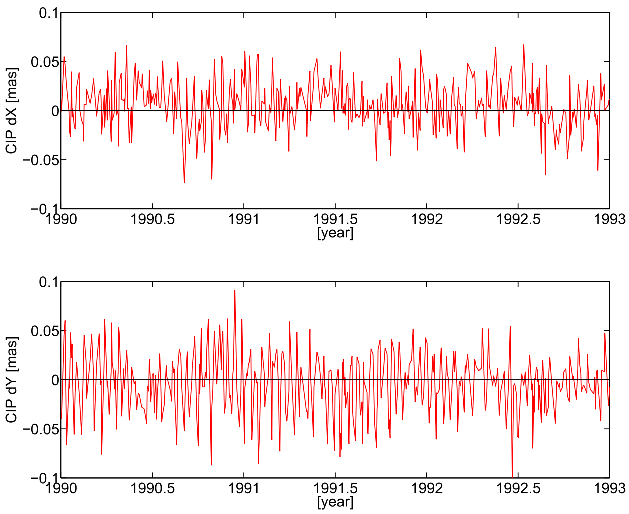

Fig. 12. Differences in estimated CPO (dX top, dY bottom) between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where UT1 variation are from the VLBI empirical model published in Artz et al. (2011): time span 1990–1993.

ERP are parametrized as piece-wise-linear functions over 24 h. For each parameter two values are estimated, one at the beginning and one at the end of a session. From these two values the offset and rate for each session were computed. The time series of the offsets is very noisy with many outliers, which we excluded in Fig. 13 to see a possible systematic signal. The offsets change at a negligible level of about 1 μs, whereas the rates change significantly with a period of one year. The periods in the UT1 time series are aliasing periods of the tidal terms with the length of the VLBI session (24 h).

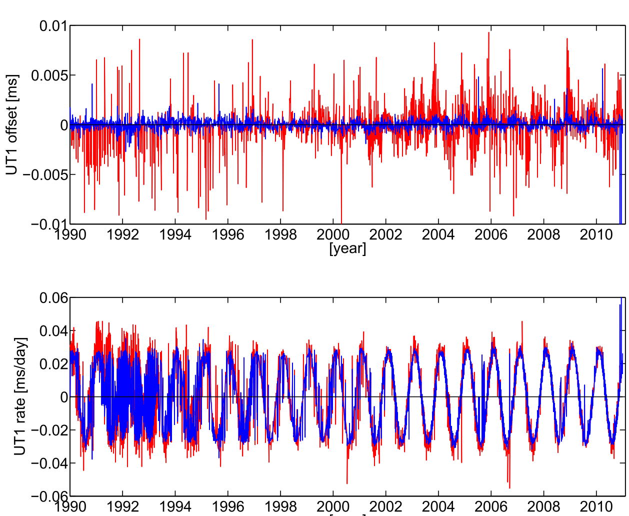

Fig. 13. Differences in estimated UT1 offset (top) and rate (bottom) between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the K1 term (23.93 h) in UT1 was changed by 10 μs (red) vs. theoretical UT1 offsets and rates computed by least-squares (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

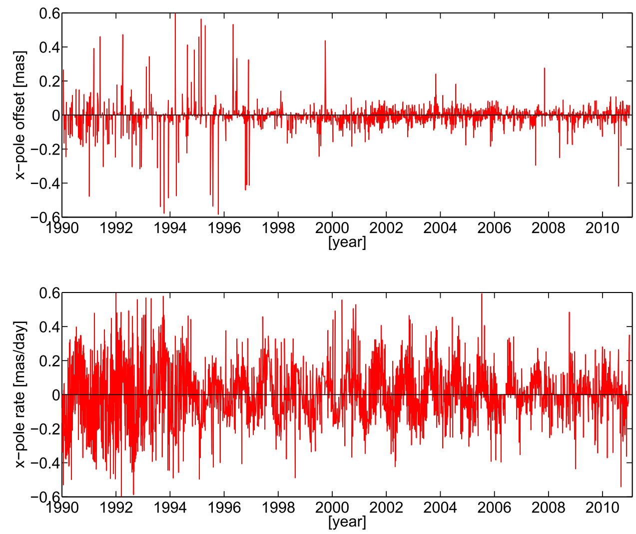

Fig. 14. Differences in estimated x-pole offset (top) and rate (bottom) between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the K1 term (23.93 h) in UT1 was changed by 10 μs.

For the full list of periods in UT1 caused by main tidal terms we refer to our previous paper (Panafidina et al., 2017). There the impact of subdaily tidal terms in polar motion on the estimated daily ERP was considered. Since the reason of the variations in both polar motion and UT1 caused by respective subdaily tidal terms is the same (the aliasing of the tidal term period with the time span of the solution), the resuting periods seen in UT1 are naturally the same as the periods seen in polar motion.

The estimated daily polar motion is influenced by a change in the subdaily UT1 as well. The offset differences are very scattered (the scatter was removed for the plots below), the rates show additionally a noisy systematic signal repeating the signal seen in the UT1 rates. In Figs. 14 and 15 we show the time series of the offset and rate differences in x- and y-pole for the case of changed K1 (23.93 h) tidal term in UT1. The amplitude of the signal in polar motion rates matches the amplitude of the signal in UT1 rate differences.

The mechanism of this effect can be explained if we consider the coordinate transformation from the terrestrial reference frame into the intermediate celestial frame, which consists of two rotations around x- and y-axis of the terrestrial frame to account for polar motion and a rotation around z-axis of the intermediate frame to account for UT1. For a single station a small rotation around the z-axis may be compensated by a pair of rotations around the x- and y-axes, i.e., an error in UT1 may be compensated by a change in pole position. For two or more stations likewise a fraction of an UT1 error may be absorbed by polar motion, depending on the inhomogeneity of the station distribution. The opposite, i.e. the absorption of a polar motion error by UT1, on the other hand is possible only in very specific situations what makes the

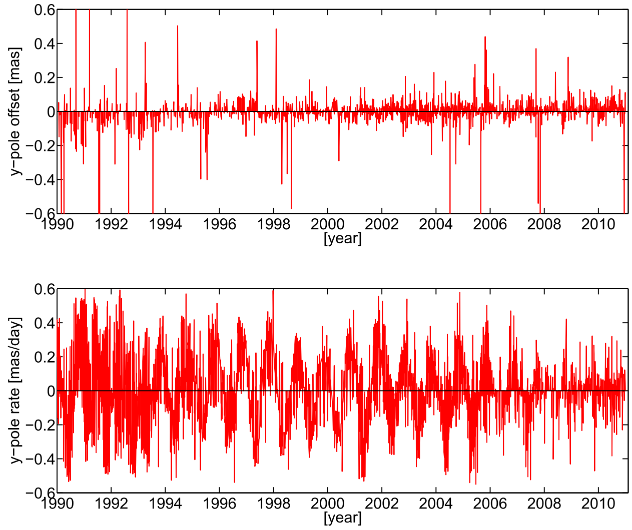

Fig. 15. Differences in estimated y-pole offset (top) and rate (bottom) between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the K1 term (23.93 h) in UT1 was changed by 10 µs.

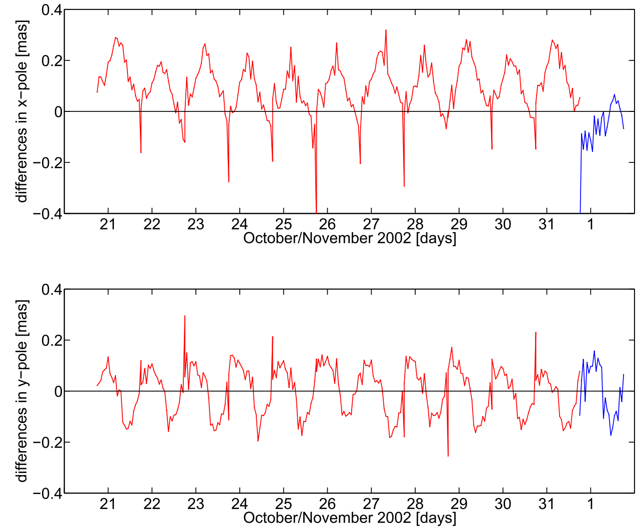

Fig. 16. Differences in estimated hourly polar motion (X-pole top, Y-pole bottom) between VLBI solutions computed with the standard IERS subdaily tidal model and with a model where the K1 term (23.93 h) in UT1 was changed by 10 µs. Red: CONT02, blue: standard R4 session. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

effect for usual VLBI solutions negligible. We showed in a previous study that an error in the subdaily polar motion model has no influence on the estimation of UT1 in VLBI solutions (Panafidina et al., 2017).

Like in case of UT1 and the nutation offsets, there is no mathematical correlation in the NEQ between the polar motion and UT1. They can be estimated together in one solution with any (reasonable) time resolution. If a priori subdaily UT1 variations are wrong in a solution, but UT1 is estimated with a subdaily resolution, all the errors in UT1 will be corrected by UT1 estimates, leaving the polar motion and the rest of the solutions unaffected.

The impact of errors in subdaily UT1 on polar motion requires more investigation. To make a first visual impression and to demonstrate the effect of uncompensated changes in UT1 on the subdaily polar motion we show in Fig. 16 the differences in hourly estimated polar motion between VLBI solutions computed with the standard subdaily UT1 model and with a model where the tidal term K1 (23.93 h) in UT1 was changed by 10 µs. The retrograde daily wave in polar motion was blocked in each 24-h solution to avoid the correlation with nutation (Hefty et al., 2000). UT1 was estimated as offset and rate once per 24 h session, thus the subdaily variations in UT1 could not be corrected by the UT1 itself. As can be seen, the subdaily polar motion varies systematically with a period of about one day in response to the daily variation in UT1. It is expected that the period corresponds to the sidereal day K1 as introduced in UT1, but it is difficult to judge about it from such a short time span as presented in the plot. This variation in hourly polar motion would lead to a noticeable variation in the polar motion rates, if they are estimated once per 24 h session.

All but the last sessions shown in Fig. 16 were taken from the CONT campaign in 2002, so that the hourly estimated polar motion is continuous and the systematic effect is seen better due to nearly the same session-setup from day to day. For comparison, the last session (marked in blue) was not belonging to the CONT campaign, it was a usual IVS-R4 session starting on the 1st of November 2002. The effect of another station setup on the response of polar motion to a change in UT1 can be well seen. This confirms our statement above that the polar motion is varying very irregularly and depends fully on the station configuration.

7. Conclusion

We showed the impact of errors in the a priori subdaily UT1 model on the CPO estimated from VLBI observations. It was found that the variations in UT1 with daily periods and the estimated nutation offsets influence each other. If the nutation corrections are kept fixed, the subdaily UT1 will absorb small errors in nutation by adjusting a sidereal diurnal wave in UT1. If the subdaily UT1 is kept fixed, the estimated nutation offsets will absorb errors in the daily variations in the speed of Earth rotation leading to systematic signals seen in the CPO time series. In practice the first situation happens only with the daily intensive 1-h VLBI sessions, which are devoted to the UT1 estimation using the observations from one baseline. In this case nearly all the parameters are kept fixed except UT1. The influence of the errors in the nutation and polar motion on the intensive UT1 values has been studied previously by several authors (Nothnagel and Schnell, 2008; Titov, 2000; Malkin, 2011). The second situation, with the subdaily UT1 kept fixed and the nutation offsets estimated, is the standard way of computing 24-h solutions within the IVS. For this reason we focused on the influence of errors in the subdaily UT1 on the estimated nutation offsets.

We demonstrated that within a usual 24-h session the observations are distributed unevenly with respect to the terrestrial frame: more observations are acquired of the quasars at some certain geographical longitudes than at other locations. Such an uneven distribution of the observations leads to a possibility for errors in the subdaily UT1 to be absorbed by nutation offsets. We provided a formula (Eq. (2)) which can be used to compute the effect in CPO produced by known changes in UT1. CPO estimates from VLBI solutions computed using different subdaily UT1 models over a time span of 22 years (1990–2011) showed a good agreement with the theoretical CPO values computed using the suggested mechanism.

To demonstrate how the connection between the subdaily UT1 model and the estimated nutation offsets works, we considered an artificial change in the subdaily UT1 of 10 μs in both sine and cosine terms and showed that it leads to a systematic signal in the CPO time series. The amplitude of the signal is about 150 μas in the beginning of the time series and getting smaller afterwards. For real VLBI solutions from years 1990–1995 the conclusion can be drawn that any errors in the subdaily UT1 variations with daily periods will propagate with the full amplitude into the nutation estimates. In the later years the effect is smaller due to a better distribution of observations, but remains systematic. To minimize or fully eliminate the effect optimum scheduling strategies should be evaluated taking into account the distribution of the VLBI observations in the terrestrial frame.

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