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Automated analysis of Kokee–Wettzell Intensive VLBI sessions—algorithms, results, and recommendations

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Abstract

The time-dependent variations in the rotation and orientation of the Earth are represented by a set of Earth Orientation Parameters (EOP). Currently, Very Long Baseline Interferometry (VLBI) is the only technique able to measure all EOP simultaneously and to provide direct observation of universal time, usually expressed as UT1-UTC. To produce estimates for UT1-UTC on a daily basis, 1-h VLBI experiments involving two or three stations are organised by the International VLBI Service for Geodesy and Astrometry (IVS), the IVS Intensive (INT) series. There is an ongoing effort to minimise the turn-around time for the INT sessions in order to achieve near real-time and high quality UT1-UTC estimates. As a step further towards true fully automated real-time analysis of UT1-UTC, we carry out an extensive investigation with INT sessions on the Kokee–Wettzell baseline. Our analysis starts with the first versions of the observational files in S- and X-band and includes an automatic group delay ambiguity resolution and ionospheric calibration. Several different analysis strategies are investigated. In particular, we focus on the impact of external information, such as meteorological and cable delay data provided in the station log-files, and a priori EOP information. The latter is studied by extensive Monte Carlo simulations.

Our main findings are that it is easily possible to analyse the INT sessions in a fully automated mode to provide UT1-UTC with very low latency. The information found in the station log-files is important for the accuracy of the UT1-UTC results, provided that the data in the station log-files are reliable. Furthermore, to guarantee UT1-UTC with an accuracy of less than 20 μs, it is necessary to use predicted a priori polar motion data in the analysis that are not older than 12 h.

Keywords: VLBI; Earth rotation; UT1-UTC; Intensives; Automated analysis

Background

The changes in the components of the rotation vector of the Earth are represented by a set of parameters called the Earth Orientation Parameters (EOP). These parameters consist of the Universal Time, polar motion, and coordinates of the celestial pole. The EOP are continually monitored and provided as time series using a combination of space geodetic techniques, of which Very Long Baseline Interferometry (VLBI) (Sovers et al. 1998) is the only one capable of measuring all the EOP directly and simultaneously. The most rapidly varying and most difficult to predict EOP is the daily rotation of the Earth, UT1, which is usually reported as difference between UT1 and UTC. In the following, we will thus refer to UT1-UTC. To provide low-latency estimates of UT1-UTC, the International VLBI Service for Geodesy and Astrometry (IVS) (Schuh and Behrend 2012) organises daily 1-h observation sessions on one extended East–West oriented baseline, the so-called IVS Intensive (INT) sessions. Currently, there are three different INT session types observed: INT1 on Monday to Friday on the baseline Kokee (Hawaii, USA)–Wettzell (Germany), INT2 on weekends using the baseline Tsukuba (Japan)–Wettzell, and INT3 on Monday mornings involving the stations at Tsukuba, Wettzell and Ny-Ålesund (Spitsbergen, Norway). When the recorded data are correlated and analysed, the resulting UT1-UTC estimates are submitted to the International Earth Rotation and Reference Systems Service (IERS) to be incorporated in the computation of the rapid EOP products.

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The aim of the INT sessions is to provide highly accurate UT1-UTC products with minimal latency. To analyse the INT sessions in a regular and reliable fashion, it is necessary to avoid the need for manual interaction. Thus, an automated analysis approach is required. For the INT2 sessions, this was successfully demonstrated using the c5++ analysis software in Hobiger et al. (2010), and these sessions have been processed in automatic mode since then.

In this manuscript, we focus on the Kokee–Wettzell baseline, i.e. the INT1 sessions, and investigate the error budget of the UT1-UTC estimate w.r.t. different analysis options and the accuracy of a priori data used. Because of the short observation duration of just 1 h and the fact that only one baseline is used in the INT1 and INT2 experiments, only a few parameters can be determined in the data analysis. Thus, in order to estimate UT1-UTC, it is necessary to have access to accurate a priori EOP as well as station positions and velocities.

Since the aim is to analyse the sessions immediately after the correlator has produced the observational files, predicted a priori EOP information has to be used for the analysis. Station positions and their linear velocities are usually sufficiently accurate in order to keep stations coordinates fixed. However, for the INT2 sessions, this might lead to difficulties due to the 2011 earthquake off the Pacific coast of Tōhoku in Japan. The earthquake caused a co-seismic displacement for the station Tsukuba, followed by an ongoing post-seismic motion, which complicates the choice of good a priori coordinates for this station.

In the following, we do not only present an automated analysis procedure for the INT1 sessions to estimate UT1-UTC with minimised latency, but we also assess different analysis configurations. We investigate the necessity of external information, i.e. weather and cable delay data extracted from the station log-files, and their importance on producing high-quality UT1-UTC estimates. Moreover, the impact of accuracy of the predicted a priori EOP is studied using extensive Monte Carlo simulations. Finally, we assess whether it is possible to additionally estimate the position of one of the stations of an INT session.

Methods

General overview on geodetic VLBI data analysis for EOP determination

The main tasks in the process of producing observables from VLBI experiment include scheduling, the experiment (simultaneous observations), correlation, and post-processing. The obtained observables are normally stored into databases, one for X- and S-band each. Currently, to solve the group delay ambiguities and to perform the ionosphere calibration, the X- and S-band databases have to be processed with CALC/SOLVE (Ma et al. 1990) or c5++ (Hobiger et al. 2010) in order to obtain an ambiguity-free and ionosphere-free X-band databases. This database can then be further analysed in order to produce estimates for various geodetic parameters, either by one of the aforementioned software, or e.g. the Vienna VLBI Software (VieVS) (Boehm et al. 2012), OCCAM (Titov et al. 2004), and GEOSAT (Andersen 2000), which all need the ambiguity-resolved and ionosphere-free databases as input.

The observational duration of VLBI sessions differs based on their purpose, but typically geodetic VLBI sessions organised by the IVS consist of either 24-h rapid turn-around (twice per week) for EOP determination or 1-h INT sessions (8 times per week) for UT1-UTC determination.

The 24-h experiments usually consist of a core network of 8 or more globally distributed stations. In such a setup, the analysis starts with solving (and distributing) the ambiguities among the observation network and computing the ionosphere correction. If the experiment is carried out successfully, i.e. the correlator is able to detect fringes, and to provide the observables (delays, delay rates), the spatial distribution and number of participating stations enables the analyst to estimate a wide selection of geodetic parameters, including EOP, station positions, and atmospheric delays and gradients. Typically, the estimation is done via some form of least-squares adjustment. The main operational purpose of the rapid turn-around experiments is to produce EOP results with a maximum latency of 15 days. On the contrary, the main purpose of the INT sessions is to produce daily estimates of UT1-UTC with minimal latency.

Analysis of intensive VLBI sessions

The INT1 and INT2 sessions are usually conducted on one baseline each and include 1 h of observations. The baselines in both experiments are oriented in East–West to make them most sensitive to changes in UT1-UTC. Hence, the analysis of the INT sessions differs from that of the 24-h sessions due to their fundamental differences in the number of stations involved and the observation duration, and subsequently the number of observations. In the analysis of INT sessions, the IVS Analysis Centres normally fix the station positions to the VLBI contribution to the International Terrestrial Reference Frame (ITRF) (Altamimi et al. 2011), e.g. VTRF2008, VTRF2013, or to an analysis centre specific global solution (IERS Operational EOP Series technical descriptions 2015). These reference frames typically account only for station position and linear velocities. Non-linear motion in the station positions is caused by phenomena such as unmodelled seasonal variation (Malkin 2013) and post-seismic motion caused by earthquakes. The latter being the situation in Tsukuba, as mentioned earlier in the manuscript.

Consequently, also the UT1-UTC estimates from INT experiments are affected by the non-linear motion. In Malkin (2013), it was shown that if these seasonal variations are ignored a systematic error exceeding 1 μs can propagate into UT1-UTC estimates from INT1 sessions. The radio source positions are normally fixed to International Celestial Reference Frame (ICRF2) (Fey et al. 2015) or to an analysis centre specific global solution (IERS Operational EOP Series technical descriptions 2015).

Due to the limited availability of telescope time for daily monitoring efforts, the INT session duration is restricted to 1 h. Thus, as compared to the 24-h sessions, there is a limited number of observations, causing that the possibility to estimate clock and atmospheric parameters is restricted. The advantage of a longer duration of 2 h has been investigated by analysing dedicated IVS-R&D sessions (Artz et al. 2012), in which the approximately doubled number of observations decreased the standard deviations of UT1-UTC by a factor of $\sqrt{2}$.

The general parameterisation for the analysis of INT sessions is presented in Table 1.

As shown in Table 1, the estimated parameters can be divided into station-dependent and session-dependent parameters, shown in the upper and lower four lines, respectively. The choice of the reference station is to some degree arbitrary, but as a general rule the station should have a stable clock and no other known problems. The clock of the reference station is not estimated while the clock for the second station is estimated by a second-order polynomial with a quadratic, a linear, and an offset term. The positions of both stations are fixed to their a priori values. The Zenith Hydrostatic Delays (ZHD) are fixed for both stations to constant values computed as function of the local surface pressure, station latitude, and orthometric height. The Zenith Wet Delays (ZWD) are estimated individually for both stations as one constant offset for the whole duration of the INT session. Radio source positions are kept fixed to ICRF2. Polar motion and nutation are fixed to their a priori values, and UT1-UTC is estimated as one offset to the a priori values. Thus, in total the number of estimated parameters in INT sessions is six. Estimation of the tropospheric horizontal gradients is not introduced into the standard analysis procedure of INT experiments due to the small number of observations. However, it is possible to compute a priori values for the gradients with external data from, e.g., numerical weather models or by estimating the gradients using observations from co-located GNSS sites. The effect of this additional information to the UT1-UTC estimation has been investigated in, e.g., Boehm et al. (2010) and Teke et al. (2015). Boehm et al. (2010) showed that the use of a priori values from direct ray-tracing or linear horizontal gradients on the Tsukuba–Wettzell baseline (INT2) did not significantly decrease the empirical standard deviations of UT1-UTC, but length-of-day (LOD) comparisons show a possibility to improve the results with direct ray-tracing. In Teke et al. (2015), the use of GNSS-derived gradients showed only small improvement in UT1-UTC accuracy. Additionally, in Nilsson et al. (2011), daily 2-h segments from the 15-day CONT08 campaign in August 2008 were used to emulate single-baseline experiments corresponding to INT1 and INT2 sessions. Even though the UT1-UTC estimate improved when analysing these segments by estimating gradients, this was mostly seen on the Tsukuba–Wettzell baseline. This is due to more dynamical weather conditions at the Tsukuba station. In order to include gradients into the near real-time analysis of INT sessions, while keeping the number of estimated parameters low, timely external data from numerical weather models are needed.

Table 1 A typical setup for the parameter estimation for an INT session

Parameter	Station #1	Station #2
Station clock	Reference	Estimate three terms (quadratic, linear, offset)
Station position	Fix to ITRF2008	Fix to ITRF2008
Zenith Hydrostatic Delay	Fix	Fix
Zenith Wet Delay	Estimate one offset	Estimate one offset
Radio sources	Fix to ICRF2	
UT1-UTC	Estimate one offset	
Polar motion	Fix to a priori	
Nutation/precession	Fix to a priori	

The weather data, mainly the local pressure, which is required to compute and estimate the tropospheric parameters, are obtained from the station log-files, if available, or from empirical/numerical weather models. The ambiguity resolution and the ionosphere correction need to be done in a similar manner as for the 24-h network experiments. However, resolving the ambiguities is simpler, since there is only one baseline in the INT1 and INT2 experiments.

Towards automated real-time analysis of Intensive sessions

The automated analysis chain with c5++ starts with the observation files (Version 1 databases) for X- and S-band in Mark3 format (Gipson 2012). These have been produced by the correlator and are converted for the analysis with c5++ to the National Geodetic Survey (NGS) VLBI data transfer format (Gordon 2007). The analysis process is shown schematically in Fig. 1. Since we start with Version 1 databases, this also means that the group delay ambiguity resolution and ionosphere correction need to be done within the automated analysis. This task is done iteratively within c5++. For this step, the atmospheric

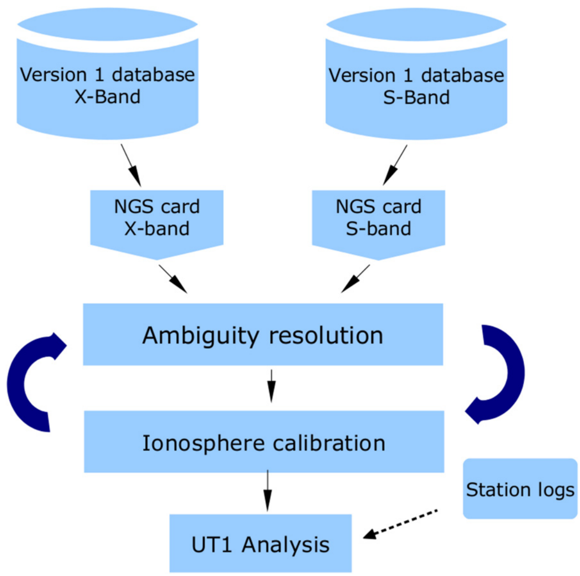

Fig. 1 Flowchart of the automated data analysis with c5++

delays are modelled using the improved versions of the Global Pressure and Temperature Model and the Global Mapping Functions (GPT2 and GMF) (Lagler et al. 2013). As stop criteria for the iterative process, we used that either the ratio of the successive weighted root mean square (WRMS) for the solution is close to unity (i.e. larger than 0.99) or that the number of iterations exceeds 20. When the ambiguities are resolved, the ionosphere delays are computed and an X-band-only observation file is written in NGS card format. The produced databases are then subsequently used as an input for all further investigations of UT1-UTC.

The estimation of UT1-UTC was carried out using different analysis setups to answer the following questions:

- Is it necessary to use the local meteorological data from the station log-files?
- What is the impact of using GMF (GPT2) or VMF1 (Boehm et al. 2006) as the mapping function?
- What is the effect of the cable delay data?
- To what degree does the accuracy of the estimated UT1-UTC depend on the a priori EOP?
- Can we simultaneously estimate UT1-UTC and one of the station positions?

In the analysis, we used a priori values for the EOP from the time series EOP (IERS) 08 C04 (Bizouard and Gambis 2011), that we will refer to as C04 in the following. This time series has however a latency of 30 days. For real-time automated analysis, the a priori values have to be obtained from a source with lower latency, such as the daily solution from the IERS Rapid Service/Prediction Centre by the United States Naval Observatory (USNO) or from the IERS Bulletin A (IERS Bulletin A 2015). The IERS rapid solution is released daily approximately at 17:05 UTC including 90 days of predictions. Bulletin A has a release frequency of 1 week and contains predicted values up to 365 days from the release epoch.

Although there were over 3000 INT1 sessions observed between January 2001 and January 2015, in total only 2071 Version 1 databases were available on the IVS data centres (IVS Data centers 2015). Our goal was to work with a homogeneous dataset, thus we selected only the INT1 sessions involving Kokee–Wettzell. This selection excluded INT1 sessions which, e.g., involved additionally Svetloe as a third station. There were also periods when Wettzell was undergoing maintenance work and was replaced by, e.g., Ny-Ålesund. The corresponding databases were not included in our analysis. Furthermore, we selected only sessions for which log-files for both stations were available on the IVS archive. Finally, 1669 out of the 2071 sessions remained and were used in the analysis.

Results and discussion

Impact of log-files and mapping functions

The 1669 INT1 sessions included in the analysis were processed to derive UT1-UTC estimates w.r.t. C04. The theoretical delays were computed following the latest IERS Conventions (Petit and Luzum 2010). Polar motion and nutation were fixed to their a priori C04 values. The station coordinates were fixed to ITRF2008 and the radio sources to ICRF2. The sessions were analysed with two different mapping functions, the Vienna Mapping Functions (VMF1) and GMF(GPT2), and with or without using the information provided in the station log-files. This implies that when no station log-files were used, the station pressure was taken from GPT2. In the following, we refer to the four different analysis options as *VMF-SL*, *VMF-NL*, *GMF-SL*, and *GMF-NL*, and a corresponding overview is given in Table 2. The use of VMF1 or GMF(GPT2) is indicated by *VMF* and *GMF*, respectively. Using or not using information from the station log-files is indicated by *SL* and *NL*, respectively.

When station log-file information was used, both mapping functions (VMF1 and GMF) used the pressure provided in the station log-files. In the cases where no station log-files were used, both mapping functions took the pressure data from GPT2. The station-dependent coefficients for VMF1 were provided by the Vienna University of

Table 2 Overview on the four analysis strategies used

Analysis strategy	Mapping function	Pressure data	Cable delay data
VMF-SL	VMF1	Station log-files	Station log-files
GMF-SL	GMF(GPT2)	Station log-files	Station log-files
VMF-NL	VMF1	GPT2	Not used
GMF-NL	GMF(GPT2)	GPT2	Not used

Technology (Vienna University of Technology. Archive of troposphere delay parameters 2015).

Wettzell was chosen as the reference station in the analysis, and no clock parameters were estimated for that station.

c5++ eliminates outlier delay values within a session according to a 3-sigma criteria. Additionally, in order to eliminate crude outliers, we used for all analysis runs a rejection criteria of 1000 µs and 50 µs for the absolute values of UT1-UTC residuals and corresponding formal errors, respectively, for each session. To ensure robustness, only sessions which appear in all configurations after the outlier elimination were included in the comparison of the results from different setups.

Figures 2 and 3 depict the UT1-UTC residuals w.r.t. C04. Also shown are the differences between the time series when the same log-file setup was used for both mapping functions.

Figures 4 and 5 depict the histograms of the UT1-UTC residuals w.r.t. C04, as well as the corresponding standard deviations for the four strategies. The UT1-UTC residuals w.r.t. C04 are expected to follow a Gaussian distribution, whereas the variances are expected to follow the chi-square distribution. Theoretical distributions are superimposed on to the corresponding histograms. The Gaussian distributions for each strategy were computed using the respective weighted biases as the mean value. The variances were computed individually from the estimates for each strategy. The distribution for the standard deviations is an empirically scaled chi distribution, that takes into account the varying degrees of freedom between the sessions. The average value of the degree of freedom was approximately 14, whereas the minimum and maximum were 4 and 29, respectively.

Based on these histograms, it can be concluded that roughly 45 and 89 % of the sessions give formal errors for the UT1-UTC for less than 10 and 20 µs, respectively, see Table 3.

Table 3 lists the statistical information for each individual solution type as well as the number of sessions that were rejected out of the 1669 sessions. In the analysis using GMF(GPT2), the difference in the number of rejected sessions when using or not using information from the station log-files is due to the rejection criteria that the formal errors were exceeding 50 µs. This is the same for the analyses with VMF1, with the exception that in two cases both the adjustment and the formal error exceeded the exclusion limits when information from the station log-files was used.

The results from these comparisons show that the WRMS w.r.t. C04 does not differ by more than 1 µs when using the two different mapping functions. Furthermore,

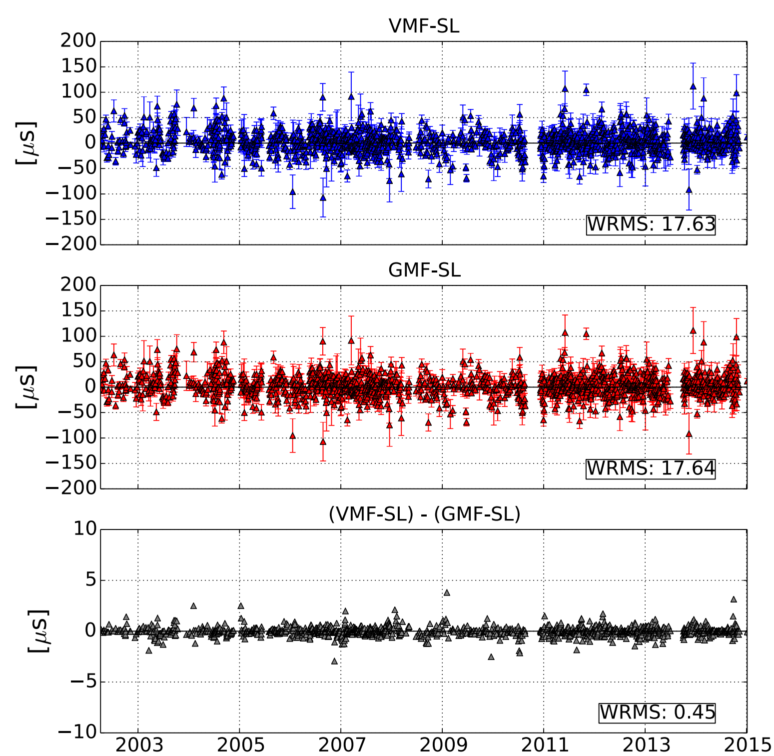

Fig. 2 Results from analyses using the information provided in the station log-files. *Top*: UT1-UTC residuals w.r.t. C04 processed with strategy *VMF-SL*. *Middle*: UT1-UTC residuals w.r.t. C04 processed with strategy *GMF-SL*. *Bottom*: Difference between results from *VMF-SL* and *GMF-SL*

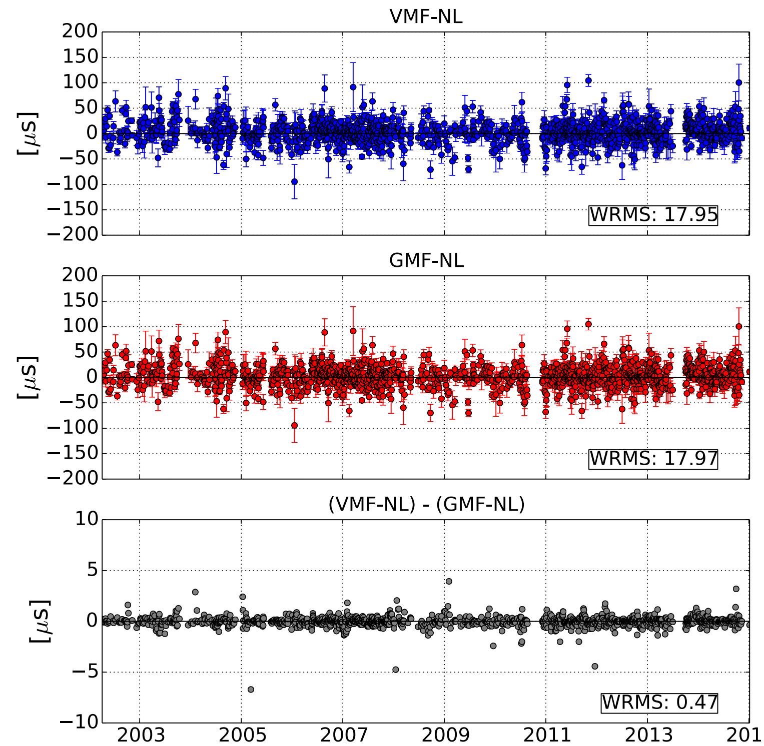

Fig. 3 Results from analyses not using the information provided in the station log-files. *Top*: UT1-UTC residuals w.r.t. C04 processed with strategy *VMF-NL*. *Middle*: UT1-UTC residuals w.r.t. C04 processed with strategy *GMF-NL*. *Bottom*: Difference between results from *VMF-NL* and *GMF-NL*

the differences between WRMS of UT1-UTC residuals with either mapping function and solutions with and without log-files are within 0.01 µs.

To reduce the dependence on external data, we chose the *GMF-NL* processing strategy for all further investigations. This choice also comes very close to the case of near real-time processing, as for this case VMF1 data are only available in their forecast version and an automated and reliable extraction of information from station log-files is not available.

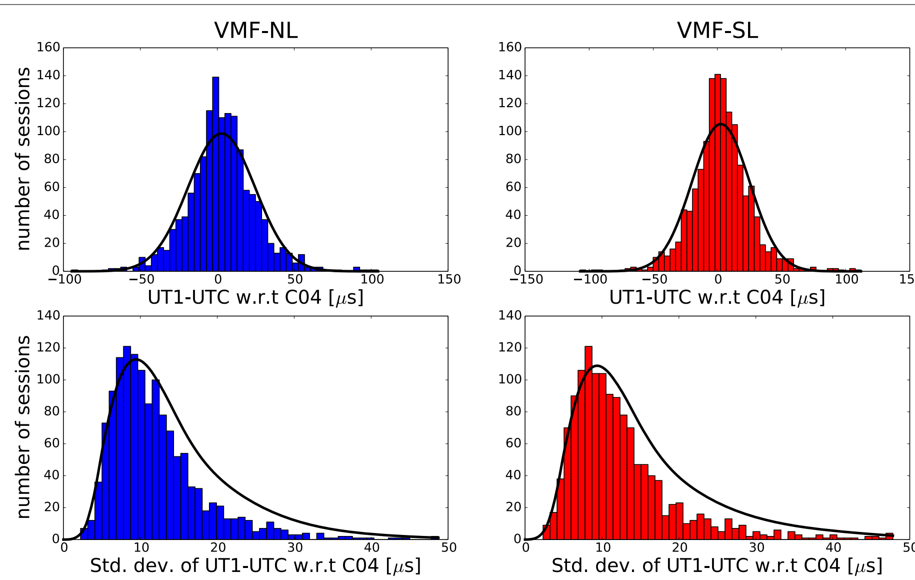

Fig. 4 Distribution of results and formal errors using VMF1. *Top*: Distribution UT1-UTC residuals w.r.t. C04 processed with *VMF-NL* and *VMF-SL*. *Bottom*: Distribution of the formal errors of UT1-UTC residuals w.r.t. C04 processed with *VMF-NL* and *VMF-SL*. The theoretical curves for a Gaussian distribution (*top*) and an empirical chi-distribution (*bottom*) are overlayed

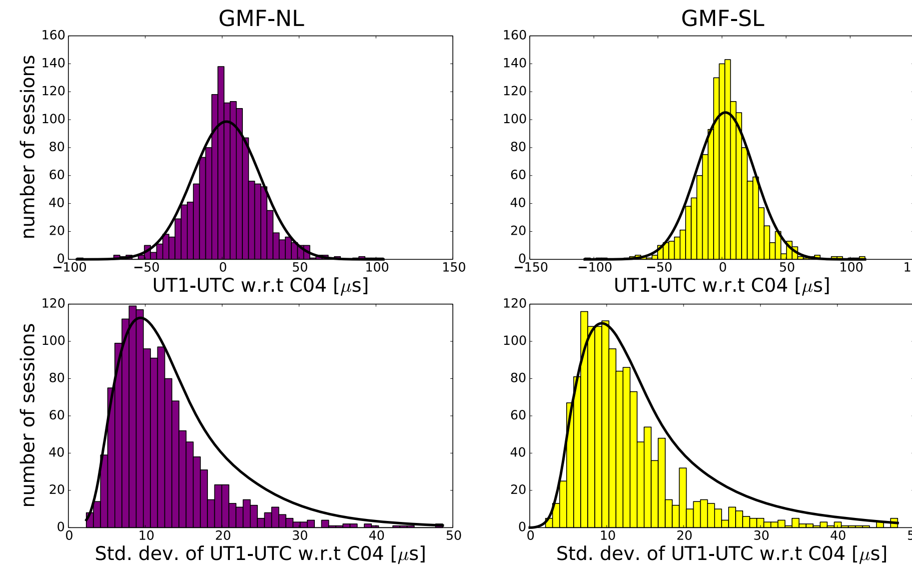

Fig. 5 Distribution of results and formal errors using GMF(GPT2). *Top*: Distribution UT1-UTC residuals w.r.t. C04 processed with *GMF-NL* and *GMF-SL*. *Bottom*: Distribution of the formal errors of UT1-UTC residuals w.r.t. C04 processed with *GMF-NL* and *GMF-SL*. The theoretical curves for a Gaussian distribution (*top*) and an empirical chi-distribution (*bottom*) are overlayed

Impact of cable delay data

Differencing the solutions obtained with analysis setups *GMF-NL* and *GMF-SL* allows to investigate the impact of using the information provided in the station log-files (i.e. cable delay and pressure data) in the analysis. The top plot in Fig. 6 depicts the difference in UT1-UTC w.r.t. C04, using analysis strategies *GMF-NL* and *GMF-SL*. Besides a few crude outliers, mainly during 2006 to 2008, the plot shows a systematic behaviour in the time-series between mid of October 2013 and February 2014. Points in this period having a difference larger than 5 µs between *GMF-NL* and *GMF-SL* are shown as red squares. The black squares denote results included in the jump period for which the difference between *GMF-NL* and *GMF-SL* is below the 5 µs limit. The rest of the data, i.e. the points outside the interval, are marked by grey circles. As the difference between solutions *GMF-NL* and *GMF-SL* can only be caused by the impact of using or not using station log data, the only question remains is which of the two external data sets, station pressure readings or cable calibration data, caused this systematic effect. Although wrong station pressure could potentially lead to systematic effects in the UT1-UTC estimates, it has to be stated that relatively large pressure errors are necessary in order to shift the UT1-UTC estimates by several µs. Empirical models of global pressure (e.g. GPT2) enable us to set a reasonably well defined range in which pressure readings stored in the station log-files should be contained. Thus, if pressure readings are outside this range, they can be easily detected and removed in order to avoid that they degrade the accuracy of the UT1-UTC estimates. Plotting the difference between solutions *GMF-NL* and *GMF-SL* against the pressure differences of GPT2 and station log pressure for each site did not reveal any indication that erroneous pressure readings could have biased solutions and shifted the UT1-UTC estimates in the period mentioned before. Thus, only the impact of cable calibration readings remains as a potential error source that could have affected the UT1-UTC estimates.

To investigate whether the systematic behaviour seen in Fig. 6 can be attributed to cable delay measurements at either of the stations, the dependence between the root mean square (RMS) of the de-trended cable readings and the UT1-UTC differences between the solution types were investigated for both stations separately. For each session/log-file pair the cable delay values were de-trended with a quadratic polynomial in order to make the nominal cable delays comparable between the stations. Figure 7 depicts the systematic dependence of differences

Table 3 Statistical information related to the four analysis strategies. Number of rejected sessions out of the total of 1669, WRMS w.r.t. C04 and weighted bias w.r.t. C04 for each solution type individually and differences for the common sessions

	Rejected sessions	WRMS [µs]	Weighted bias [µs]	$\sigma_{\text{UT1-UTC}}$ <10 µs	$\sigma_{\text{UT1-UTC}}$ <20 µs
VMF-SL	311	17.63	2.65	44.92 %	88.43 %
GMF-SL	311	17.64	2.65	44.77 %	88.66 %
VMF-NL	263	18.03	2.65	44.87 %	89.90 %
GMF-NL	263	18.04	2.67	44.67 %	89.83 %

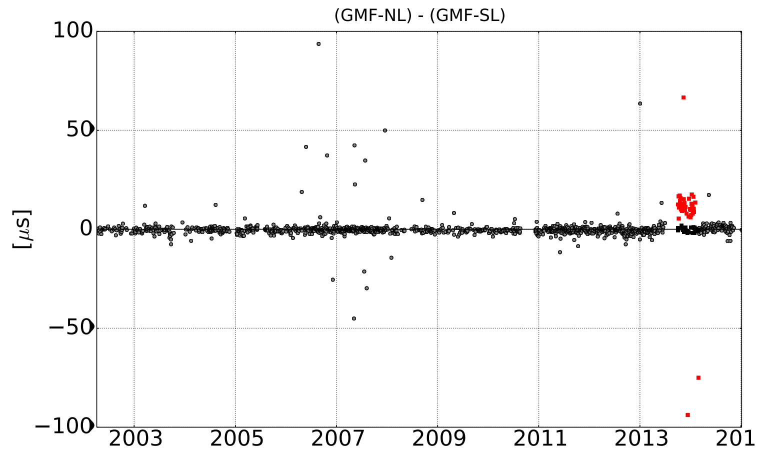

Fig. 6 The differences between the UT1-UTC estimates obtained with analysis strategies *GMF-NL* and *GMF-SL*. Differences larger than 5μs during October 2013 to February 2014 are shown as red squares

between the UT1-UTC residuals for *GMF-NL* and *GMF-SL* on the corresponding RMS of cable delay of Kokee station on the left, and of Wettzell station on the right, respectively. The markers for the data points follow the same logic as explained earlier with Fig. 6.

The scatter plot for Wettzell shows clearly that all of the jump points are correlated with high RMS values for the cable delay. The majority of the cable delay RMS values are below 5 ps, whereas the jump points have an RMS value centred between 15 and 20 ps. For Kokee, no similar dependence can be seen as all the corresponding points lie within the normal RMS of cable delay range for the station. Thus we can conclude that apparent problems with the cable delay readings in the Wettzell station log-files are the cause for the jump in the difference of the UT1-UTC residuals w.r.t. C04.

Because the aim of our work is to analyse INT sessions automatically and in near real-time, outliers in the station log-files can cause various problems. The automation requirement makes it difficult to detect any suspicious readings in the station log-files. Furthermore, due to software or hardware errors, station log-files may contain lines of non-standard output, which can cause further problems in the automated analysis. Thus, for the standard non-automated IVS processing, the station log-files are usually screened manually (Gipson 2015, personal communication) or processed with a semi-automatic program (Thorandt 2015, personal communication) so that suspicious or wrong cable calibration data do not propagate in the analysis.

Due to these possible complications and since the advantage in terms of WRMS of the UT1-UTC residuals

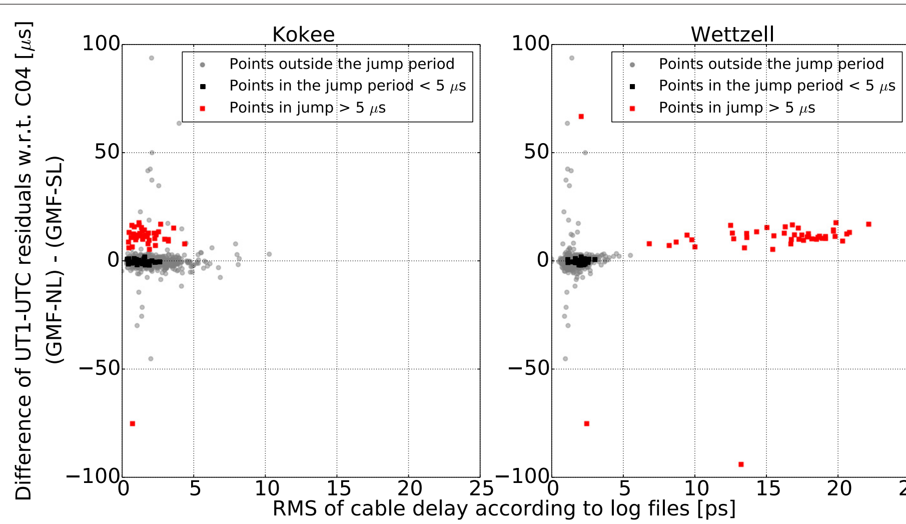

Fig. 7 Differences in UT1-UTC residuals vs RMS of cable delays. Shown are (*GMF-NL*)–(*GMF-SL*) against the corresponding RMS of cable delays for Kokee (*left*) and Wettzell (*right*), respectively

is relatively small, we decided to perform the analysis presented in the following sections using the *GMF-NL* analysis setup. The same outlier criteria as used before were applied for consistency.

The impact of a priori EOP information

For the INT sessions, only the UT1-UTC parameter can be estimated while the other EOP have to be kept fixed on their a priori values. Furthermore, the low latency automated analysis of the INT sessions requires predicted EOP since no better information is available in near real time. It is thus important to investigate the errors that propagate from any inaccuracy of the predicted a priori EOP information to the UT1-UTC estimates.

The impact of a priori celestial pole offsets

The impact of celestial pole offsets (CPO) on the accuracy of UT1-UTC estimates has been investigated by Malkin (2011). CPO describe corrections to the IAU 2000/2006 models for precession and nutation and are attributed, e.g., to errors in precession and/or very low-frequency nutation terms, as well as the free nutation of the Earth's liquid core (free core nutation (FCN)) (Malkin 2007). CPO are only available as results from data analysis either as empirical corrections or models fits. Malkin (2011) showed that neglecting CPO-models in the analysis of INT sessions can lead to systematic influences in UT1-UTC of about 1.4 μs.

In our analyses, we use a priori EOP from C04. This means that empirical CPO corrections are included in our analysis already.

The impact of a priori polar motion

The impact of polar motion on the accuracy of UT1-UTC estimates has been previously investigated in Nothnagel and Schnell (2008), where it was shown that offsets in polar motion have a directly proportional effect on the UT1-UTC estimates.

As mentioned earlier, for automated real-time analysis of INT sessions, polar motion predictions have to be used. These are provided, e.g., by the IERS Bulletin A. Bulletin A has two different solution types, daily and weekly. They are products of the IERS Rapid Service/Prediction Centre (IERS Rapid Service Prediction Centre 2015), released daily approximately 17:05 UTC and weekly on Thursdays, respectively. Bulletin A provides the polar motion components x_p and x_y as well as UT1-UTC at daily intervals. We consider both cases where the predictions are in the worst case 1 day or 6 days old, corresponding to the daily and weekly Bulletin A. For both cases, we assume the prediction accuracy model provided in the weekly Bulletin A. According to the model, the accuracy of predicted polar motion in μas can be described by

$$\sigma_{X_p}, \sigma_{Yp} = 680 \cdot D^{0.80}, \tag{1}$$

where D is the number of days elapsed since the Bulletin was released. Thus, for the Bulletin A daily solution, the D is at the most 1 day, whereas for the weekly Bulletin A the maximum is 6 days.

Using Eq. 1, the impact of the accuracy of the polar motion on the UT1-UTC estimation was studied with extensive Monte Carlo simulations. The simulations were carried out by adding offsets to the a priori polar motion from C04. These offsets were determined by drawing random values from a normal distribution with zero mean and a standard deviation that is equal to the uncertainty stated in Eq. 1. The prediction period of Bulletin A was divided into 24 time steps of each 0.25 day between 0.25 and 6 days. Additionally, the 1-day prediction period for the daily solution was further divided into 0.0625 day steps. In the Monte Carlo simulations, for each of the 1669 sessions, a random offset value for the polar motion was determined 20 times for each time step, and successively UT1-UTC was estimated from analysis of the session. This resulted in that more than 1,200,000 analyses were performed. A WRMS of the UT1-UTC residuals w.r.t. C04 was computed for each of the 20 runs per time step. These 20 WRMS values were then averaged, thus yielding a total of 36 averaged WRMS values, and their standard deviations were computed to represent a measure of uncertainty.

The results of the Monte Carlo simulations are presented in Fig. 8. A power function was fitted to the data points. The adjustment to determine coefficients of the fit was weighted with the standard deviations computed for the WRMS values. Furthermore, the fit was forced to intersect with the 0-day WRMS value which was taken to be 18 μs, as obtained with the *GMF-NL* analysis strategy.

From this it can be seen that the mean WRMS of the UT1-UTC residuals w.r.t. C04 increases steadily as polar motion accuracy declines when the Bulletin A epoch ages. After 1 day, the mean WRMS has increased by 4 to 22 μs, and after 3 days, the value has doubled relative to the standard solution. With the maximum number of days elapsed since the Bulletin A epoch the mean WRMS of the UT1-UTC residuals surpasses 53 μs. During the daily solution interval, the WRMS of UT1-UTC residuals increase 8 and 20 % after 12 and 24 h, respectively. The predicted a priori polar motion information must not be older than 12 h in order to achieve a WRMS of below 20 μs. In order to attain degradation of less than 5 % in the accuracy of the UT1-UTC estimates, a priori polar motion would have to be known with a latency of 6 h. If the estimated accuracy level of the a priori values is known, any conclusions about the impact of using a priori polar motion from sources such as International GNSS Service (IGS) (Dow et al. 2009) Ultra-Rapid solution (IGS Products 2015) on UT1-UTC accuracy can also be drawn from Fig. 8.

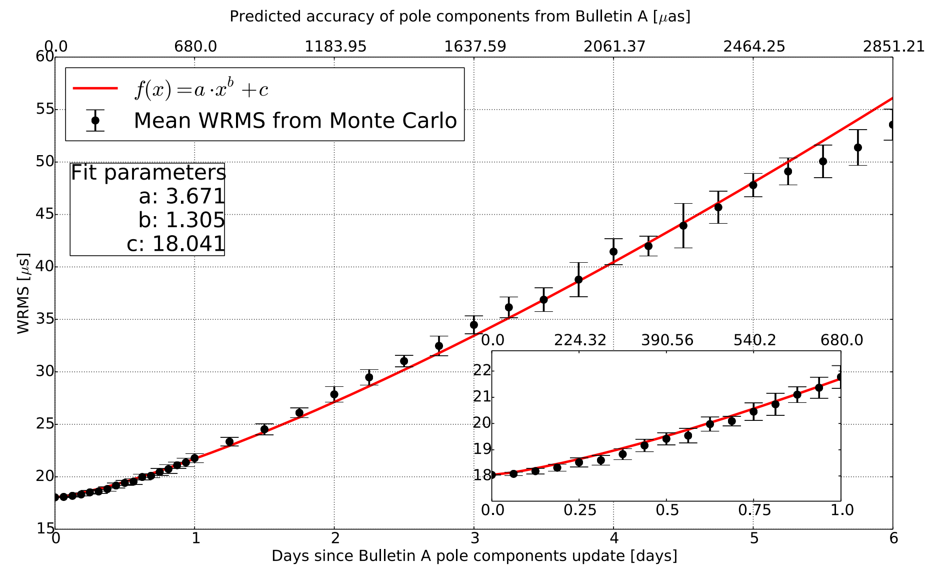

Fig. 8 Mean WRMS of UT1-UTC residuals w.r.t. C04. The *X*-axis shows days elapsed since the Bulletin A epoch (*bottom*) and corresponding polar motion accuracy (*top*)

This shows that outdated polar motion information has a strong impact on the accuracy of the UT1-UTC estimate. This result is in good agreement with the theoretical analysis presented in Nothnagel and Schnell (2008).

The impact of a priori UT1-UTC accuracy

Similar Monte Carlo simulations as described in the previous subsection were carried out to investigate the effect of UT1-UTC accuracy to the estimation process. According to Bulletin A, the accuracy of predicted UT1-UTC values in μs can be described by

$$\sigma_{UT1} = 250 \cdot D^{0.75}, \tag{2}$$

where D is defined similarly as in Eq. 1. The number of simulations and the prediction interval was the same as for the polar motion, excluding the densified simulations on the 1-day interval, i.e. 20 simulations per time step from 0.25 to 6 days in 24 steps, yielding more than 800,000 analyses. The results of the simulations are presented in Fig. 9. It is shown that the age of the a priori UT1-UTC values do not have any noticeable impact on the estimated UT1-UTC. In general, the estimates do not differ whether UT1-UTC a priori information was more or less accurate. The WRMS stays at a constant level during the whole 6-day period and with a variation that is much lower than the error margins determined from the Monte Carlo runs. This can be attributed to the fact that, like in any least-squares adjustment, small changes of an a priori value always lead to the same estimated value of this parameter. However, this requires the functional model to be either linear in the particular parameter or the linearisation of the parameter still be a good enough approximation for the difference between the "true" value of the parameter and its a priori value. Such a condition seems to be fulfilled for even very outdated a priori UT1-UTC values.

Impact of estimating station position

In a standard INT session, analysis station positions are usually kept fixed to their a priori values for both stations. In the group delay ambiguity resolution step of the analysis, even if the a priori station coordinates are not highly accurate, this has no effect on the ambiguity resolution since the ambiguity spacing is considerably larger than the uncertainty in the station position. To study whether fixing the station positions is the only approach when estimating UT1-UTC, we investigated the effect of estimating the non-reference station position with varying constraint levels. The 1669 sessions were analysed keeping one station as the reference while the position of the other station was estimated using constraints. The applied constraints were between 0.1 and 10 mm, equally distributed on a logarithmic scale. All other parameters were estimated as in the previous section where we investigated the impact of log-files and mapping functions. Figure 10 depicts the effect of the station position estimation of Kokee on the WRMS of the UT1-UTC residuals w.r.t. C04 as a function of the constraint levels when Wettzell was kept as the reference station. The secondary Y-axis on the right-hand side shows the number of sessions that failed when the Kokee station position was estimated. As the constraint level is loosened, sessions are lost, which is due to that solutions did not converge within the maximum limit of 20 iterations. The results show that there is no degradation in the UT1-UTC estimate if constraints on the station

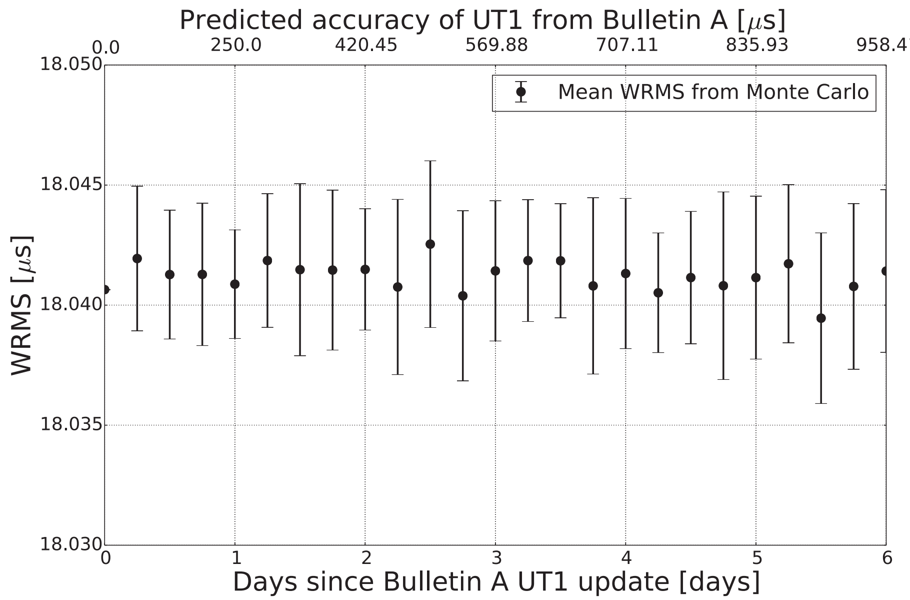

Fig. 9 Mean WRMS of UT1-UTC residuals w.r.t. C04. The *X*-axis shows days elapsed since the Bulletin A epoch (*bottom*) and corresponding UT1-UTC accuracy (*top*)

position on the millimetre level are applied. However, with a constraint level looser than 1 mm, we notice an increase in the WRMS of the UT1-UTC residuals w.r.t. C04, and a larger number of solutions to either become singular or to be rejected.

Conclusions

Our results confirm that INT sessions can be analysed automatically in near real time and it is possible to obtain accurate UT1-UTC estimates from the analysis. Currently c5++ is already used regularly by the Geospatial Information Authority of Japan (GSI) to provide fully automated analysis of INT2 sessions. Based on the experience gained in this study, we consider to perform in the future an automated analysis of the INT1 sessions using c5++ in order to provide daily near real-time UT1-UTC.

We find that the choice of using either VMF1 or GMF as mapping function does not have a significant effect on

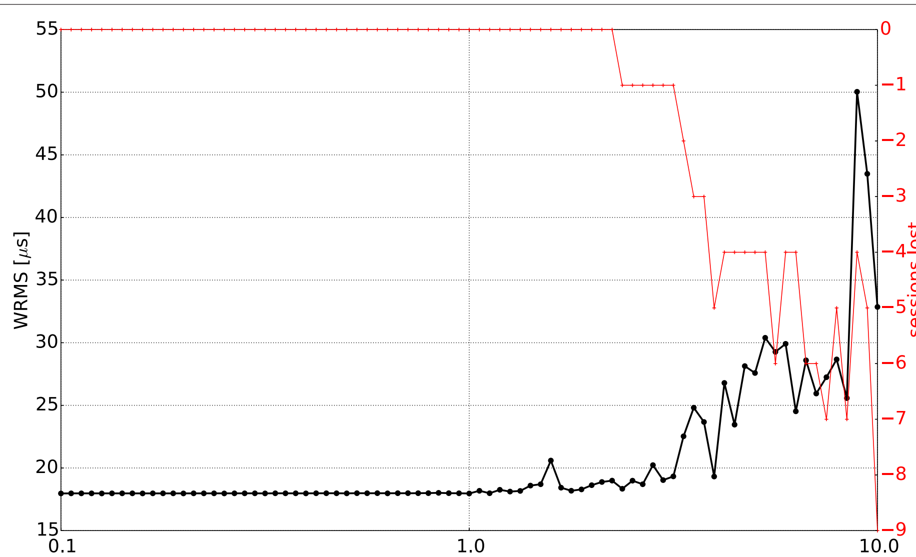

Fig. 10 Impact of station position estimation. The *black line* depicts the WRMS of UT1-UTC residuals w.r.t. C04 (*left scale*) as a function of the constraint level for the station position estimation of Kokee. The *red line* depicts the number of sessions that failed when the station position was estimated (*right scale*)

the accuracy of the UT1-UTC results. When comparing the WRMS of the UT1-UTC residuals derived from four different analysis strategies with different mapping functions, different pressure data, and with or without cable delay data, the differences between the WRMS remain on the order of 0.01 μs. Using meteorological and cable measurements from the station log-files gives a slightly lower WRMS value for the UT1-UTC residuals. The corresponding WRMS reduction is less than 1 μs. However, using the station log-file information caused the formal error of 48 sessions to exceed the outlier criterion of 50 μs. These 48 sessions were excluded from the WRMS calculation. Consequently, there is a benefit in using station log-files, provided that the weather and cable delay data are reliable. This poses a challenge when the analysis is done in fully automated mode without human interaction to screen the log-file data for outliers and bad data.

Our work shows that correct cable delay readings are of importance and large RMS of the cable delay data can lead to offsets for the UT1-UTC results. Otherwise, neglecting cable calibration data seems to have almost no effect on the results when using the particular two stations investigated in this study. However, from a more general point of view, electrical path length changes at other sites that might be involved in the future in INT sessions might show characteristics that require such external data in order to process the observations in an unbiased way.

We can conclude from our investigations that the most significant impact on the possible accuracy of the UT1-UTC estimates is due to the availability of recent polar motion values. In order to reach an UT1-UTC accuracy of 25 μs or better the a priori polar motion values from Bulletin A must not be older than 1.5 days. To achieve UT1-UTC with an accuracy of less than 20 μs, the a priori polar motion from Bulletin A can not be older than 12 h. Furthermore, to guarantee a degradation of less than 5 % in the accuracy of the UT1-UTC estimates, a priori polar motion information would be needed with a latency of less than 6 h. If however the difference between the experiment observation time and the Bulletin A epoch exceeds 1 day, we quickly see that the polar motion uncertainty starts to dominate the UT1-UTC estimate accuracy. On the other hand, the accuracy of the UT1-UTC estimates is not impacted by the uncertainty of the available a priori UT1-UTC values. Based on these investigations, we can conclude that out of all studied factors the most significant in producing accurate UT1-UTC products is the availability of daily polar motion values.

In agreement with other studies, for example Boehm et al. (2010), we conclude that the current level of accuracy of today's INT sessions is around 17 μs for UT1-UTC. It seems hard to imagine that this situation can be improved unless fundamental changes in the strategy for the INT sessions are implemented. One step forward would be to increase the number of observations as pointed out by Artz et al. (2012). In doing so, the expectation is that not only the precision of the UT1-UTC will increase, but also its accuracy. Another potential for improvement might be found in sophisticated scheduling algorithms, as presented by Leek et al. (2015). In general, the next-generation VLBI system, VGOS (Petrachenko et al. 2012), promises improvements due to for example broadband observations with fast-slewing telescopes. As a part of VGOS, seamless and reliable archives of station-related parameters, in particular meteorological data and cable delay data, are anticipated (Neidhardt 2015, personal communication) which will help the real-time automated analysis. Furthermore, refined analysis approaches, e.g. considering correlation between the observations (Gipson 2006) and an advanced stochastic model (Tesmer and Kutterer 2004), might lead to further improvements.

Competing interests

The authors declare that there are no competing interests.

Authors' contributions

NK performed all data analysis, prepared the graphical material, and wrote the manuscript. TH and RH supervised NK and helped to improve the manuscript. All authors read and approved the final manuscript.

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