Fully automated VLBI analysis with c5++ for ultra-rapid determination of UT1

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VLBI is the only space-geodetic technique which gives direct access to the Earth's phase of rotation, i.e. universal time UT1. Beside multi-baseline sessions, regular single baseline VLBI experiments are scheduled in order to provide estimates of UT1 for the international space community. Although the turn-around time of such sessions is usually much shorter and results are available within one day after the data were recorded, lower latency of UT1 results is still requested. Based on the experience gained over the last two years, an automated analysis procedure was established. The main goal was to realize fully unattended operation and robust estimation of UT1. Our new analysis software, named c5++, is capable of interfacing directly with the correlator output, carries out all processing stages without human interaction and provides the results for the scientific community or dedicated space applications. Moreover, the concept of ultra-rapid VLBI sessions can be extended to include further well-distributed stations, in order to obtain the polar motion parameters with the same latency and provide an up-to-date complete set of Earth orientation parameters for navigation of space and satellite missions.
Key words: VLBI, Earth rotation, UT1, ambiguity resolution, automation.

1. Introduction

Very Long Baseline Interferometry (VLBI) is the only space geodetic technique which allows a determination of all components of Earth rotation. The daily Earth rotation phase UT1 is the most variable quantity which is only partly predictable due to its complicated physical nature. Since the early 1980s, routine experiments have been carried out in order to determine this quantity, using a network of globally well-distributed antennas. In the recent years dedicated one-hour single baseline sessions, up to 7 times a week, have been established, with the goal of providing estimates of UT1 with much lower latency. Although the turn-around time of these so-called Intensive experiments has been improved greatly, there are still bottlenecks in the processing chain which prevent access to UT1 within a few minutes after the last scan has been observed. Thus dedicated ultra-rapid UT1 sessions were conducted in order to demonstrate that real-time determination of UT1 becomes possible when automated processing routines are applied.

2. Ultra-rapid UT1 Sessions

Sekido *et al.* (2008) demonstrated that the usage of high-speed internet connections allows the determination of UT1 within an hour after the last scan has been recorded. Based on this technology, Matsuzaka *et al.* (2008) reported the fastest determination of UT1, achieved in less than four minutes after the session was completed. Such low-latency results were not only possible because of the excellent network infrastructure but also because the geodetic analysts were transforming the correlator output into observational files and then conducted the parameter estimation. Tasks like ambiguity fixing and ionospheric correction had to be done manually, and the UT1 estimation process itself had to be started afterwards. Two different analysis packages, namely CALC/SOLVE (Baver, 2010) and OCCAM (Titov *et al.*, 2004) were used in parallel to evaluate their usefulness for automated processing of single-baseline UT1 experiments. CALC/SOLVE is capable of resolving ambiguities via a built-in module, but requires user-interactions to carry out this step. The user has to identify the ambiguities via a graphical user interface and shift them to a common level. The OCCAM software does not have the capability to carry out ambiguity resolution, but Koyama *et al.* (2008) have developed a variety of scripts which overcome this drawback, by separate analysis of X- and S-band data, before fixing the ambiguities and computing the ionosphere corrections. Although this quite cumbersome solution allows partial automation of the analysis, it does not provide a straightforward way to access the correlator output nor is it capable of outputting results in a format that can be submitted directly to the International Earth Rotation and Reference Systems Service (IERS).

3. c5++ and VLBI

Otsubo and Gotoh (2002) have developed an analysis software package based on Java named CONCERTO4 which enabled the user to consistently process SLR, GPS

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and other satellite tracking data. Driven by the need to update the software and replace the existing Java code, VLBI was added as an additional module by this analysis package c5++. Other than single technique analysis packages, c5++ also provides state-of-the-art modules for a variety of geodetic, mathematical and geophysical tasks that can be combined to a stand-alone VLBI application. Although many of these modules can be used for any of the space geodetic techniques, a couple of technique specific solutions (like relativity, antenna deformation, etc.) had to be coded exclusively for VLBI.

4. Automated Analysis

Large parts of the VLBI analysis chain can be automated with existing software packages, but a few stages remain as bottlenecks which require manual input from the analyst. As shown in Fig. 1 and discussed in Sekido *et al.* (2008), observational data is sent via high-speed network to the correlator. The correlation results of all channels are combined within bandwidth synthesis and X- and S-band delays are stored for further processing. Until now, so-called VLBI databases for geodetic analysis had to be created manually by collecting and sorting the delays from the correlator and merging it with the log file information, i.e. meteorologic data and cable calibration information. Nevertheless, since c5++ can directly interface both correlator output and log files, this step can be automated in order to provide an initial database for VLBI analysis.

4.1 Ambiguity resolution

Due to the fact that current geodetic VLBI systems do not observe broadband delays, but rather sample the covered observing band by several narrow channels, the obtained delays contain an unknown number of integer ambiguities. Thereby, the ambiguity spacing is equal to the reciprocal of the unit spacing of all channels belonging to one observing band. Ambiguity estimation in VLBI is an iterative process that involves the computation of a simplified geodetic solution, shifting of the ambiguities according to the residuals obtained and an update of the resulting ionosphere correction, which depends on the selection of the X/S band ambiguities. Usually, the ambiguities are assigned to the ionosphere free linear combination, which has the drawback that the ambiguity spacing becomes a non-integer number. The c5++ implementation of the ambiguity estimation algorithm does not follow this procedure, but introduces X- and S-band delays as independent observations. Thus, the integer nature of the ambiguities does not change, but the ambiguity shifting based on the residual must be split according to the spacing of each band. Shifting the ambiguities and simplified geodetic adjustment is iterated as long as the residuals do not exceed the corresponding ambiguity spacings. This approach will work properly only if the ionosphere delay does not exceed the ambiguity spacing defined by the X/S band set-up. Figure 2 shows an example of a successful ambiguity resolution based on INT2[1] data.

4.1.1 Optimum choice of the functional model In order to estimate the ambiguities the following function

[1]One hour UT1 sessions on the baseline Wettzell-Tsukuba are named INT2.

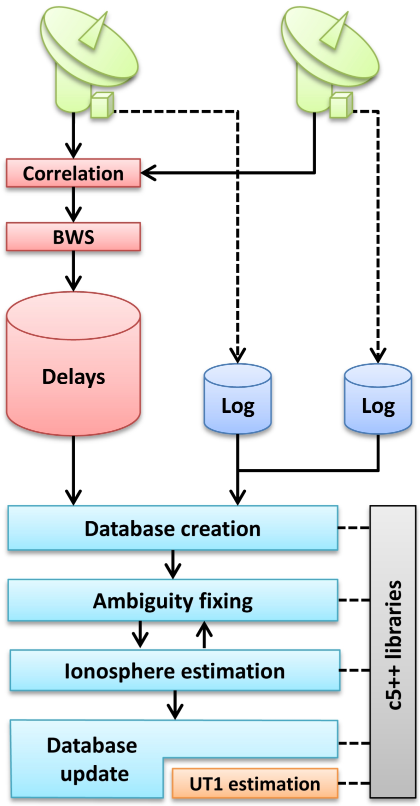

Fig. 1. Data flow in automated VLBI processing (abbreviations: band width synthesis (BWS), station log information (Log)).

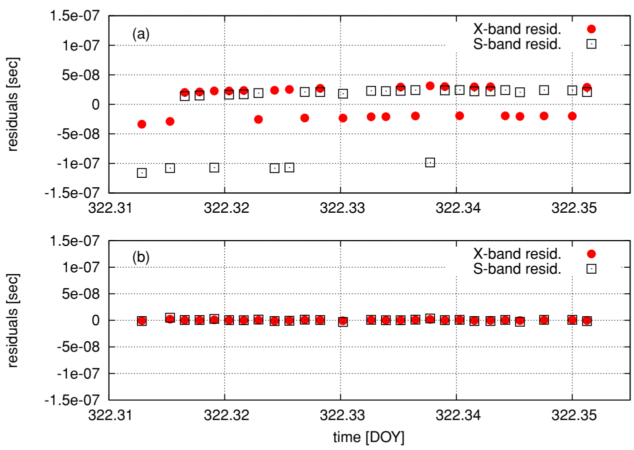

Fig. 2. Residuals after first (a) and sixth (b) iteration of the ambiguity resolution algorithm for an INT2 experiment in 2007. All residuals in the sixth, i.e. last iteration (Fig. 2(b)) are much smaller than the corresponding ambiguity spacing (i.e. 50 ns at X-band and 125 ns at S-band) and thus it can be assumed that all ambiguities are detected properly.

model can be set up

$$\tau_x(t) - \tau_{th}(t) = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 \qquad (1)$$

$$\tau_s(t) - \tau_{th}(t) = b_0 + a_1(t - t_0) + a_2(t - t_0)^2 \qquad (2)$$

where $\tau_x(t)$ and $\tau_s(t)$ denote the measured X- and S-band delays. The difference between the theoretical delay $\tau_{th}(t)$ is assumed to be modeled properly by setting up a polynomial for the clock function, represented by a quadratic

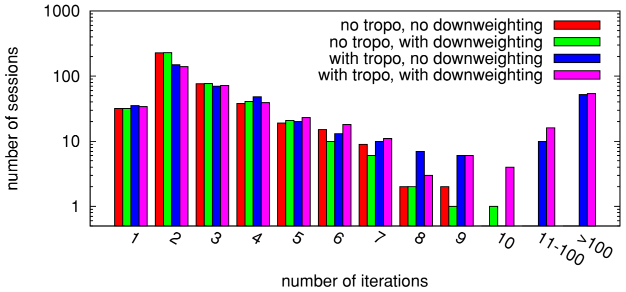

Fig. 3. Number of iterations that are required to fix ambiguities for 420 INT2 sessions between Jan. 1st, 2006 and May 30th, 2010. Four different processing strategies have been tested. Red and green bars denote results based on Eqs. (1) and (2), blue and purple bars show results when the functional model is extended by wet-troposphere delay estimation. Each run was made with and without elevation dependent down-weighting. The vertical axis is scaled logarithmically for better readability.

polynomial with coefficients a_0, a_1 and a_2. Equations (1) and (2) share the same unknowns except the constant clock offset (a_0 resp. b_0) which is assumed to be different for each band due to ionosphere delays. In order to find out how different variants of this approach perform, tests with real data from 420 INT2 sessions between Jan. 1st, 2006 and May 30th, 2010 have been performed. Four different processing strategies were investigated and the number of iterations that are necessary to resolve the ambiguities was taken as a measure to judge which approach suits best for unattended and automated operation. In the first run, it was assumed that wet troposphere delays are much smaller than the ambiguity spacing defined by the X/S band combination and thus can be neglected. In the second run, wet delays were estimated in addition to the models described in Eqs. (1) and (2) where the Global Mapping Function (Boehm *et al.*, 2006) was used for modeling that part. Both approaches were tested without and with down-weighting the observations depending on their elevation angles.

From the results shown in Fig. 3 it can be seen that an inclusion of the troposphere delays leads to an increase in the number of iterations and even causes some of the sessions not to converge at all. This can be explained by the fact that due to the small number of observations for the Intensive experiments, an increase in the number of unknowns reduces post-fit residuals and prevents successful detection of the ambiguity shifts. Moreover, down-weighting seems to lead to a slightly worse performance. For the case that only a simple clock model with 4 parameters is used, all ambiguities can be estimated with at most 10 iterations in a fully automated fashion. Thus this approach will be used for the automated UT1 estimation described in the following sections.

4.2 Ionosphere correction

Once all ambiguities have been fixed, X- and S-band data can be combined and an ionosphere correction for each observation can be determined. Since the choice of the ambiguity reference is arbitrary for single baseline sessions, the ionosphere correction will be affected by this choice. Nevertheless, as this constant will later be absorbed in the clock-offset it does not harm the estimation of the target

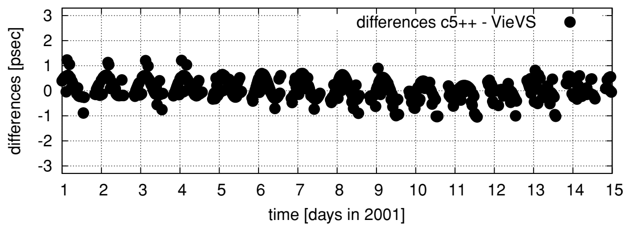

Fig. 4. Differences of total theoretical delay for the baseline Westford-Wettzell between c5++ and VieVS as obtained within DeDeCC.

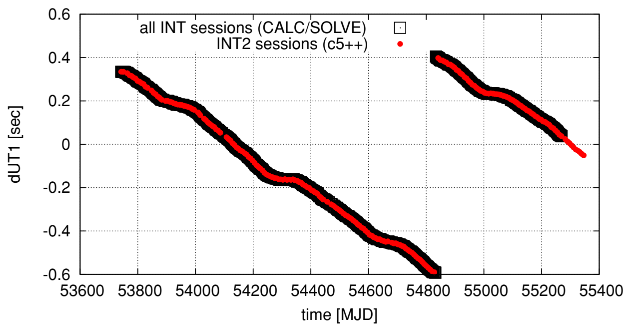

Fig. 5. UT1 from all Intensive VLBI sessions computed by GSI with CALC/SOLVE (black) and the fully automated c5++ results as described in Fig. 1.

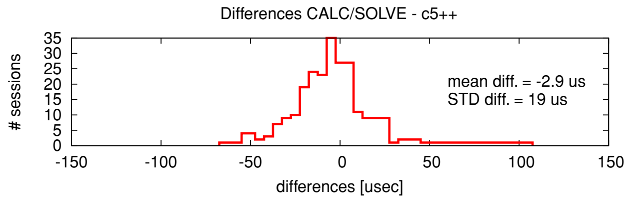

Fig. 6. Differences (CALC/SOLVE–c5++) of estimated UT1 for all common INT2 experiments (see Fig. 5).

parameters.

4.3 UT1 computation

Based on the ionosphere-free X-band observations, one can estimate UT1 from the single baseline VLBI observations. Station coordinates are kept fixed to the ITRF2008[2] nominal values and the theoretical delays are computed in accordance with the latest IERS Conventions (McCarthy and Petit, 2004). Wet troposphere delays, a quadratic clock model (similar to the one described in Eq. (1)) as well as a UT1 offset are parametrized for the least-squares adjustment. The latter value represents an average difference between the Earth orientation's phase as measured by VLBI and the one based on a-priori information. Thus, adding the estimated offset to an UT1 value based on a-priori information for the middle of the session, gives the final estimate of UT1 for that session.

5. Software Validation

To make sure that all modules of c5++ are properly debugged and consistent with state-of-the-art geophysical models, an effort was made to validate the software against other VLBI packages. Therefore c5++ derived results were

[2] http://itrf.ign.fr/ITRF_solutions/2008/.

submitted to the "Delay and Partial Derivatives Comparison Campaign" (DeDeCC), (Plank *et al.*, 2010) in order to determine how the theoretical models of this software package differ from those of other analysis packages. DeDeCC requires the contributors to submit their theoretical delays for a single baseline, i.e. Westford-Wettzell, using a given observing schedule and Earth rotation parameters. Figure 4 shows the results from a comparison between c5++ and VieVS (Spicakova *et al.*, 2010) within DeDeCC. The obtained differences are well within one picosecond (or 0.3 mm) which is much below the measurement accuracy of existing and planned VLBI systems. Thus, based on this external validation, it can be concluded that c5++ is able to provide theoretical VLBI delays with up-to-date geophysical models which are consistent with other analysis packages. Following this evaluation, UT1 estimation was implemented in c5++ knowing that no significant model biases from the software can propagate into the estimates.

6. Results

To test the fully automated UT1 processing scheme described in the prior sections, correlator output (i.e. bandwidth synthesis results) and station log files for all INT2 sessions between Jan. 1st, 2006 and May 30th, 2010 were obtained from the Geospatial Information Authority of Japan (GSI). This kind of information represents the usual output that is used for ultra-rapid determination of UT1. On the contrary, UT1 results from Intensive sessions computed with an independent analysis software are available from GSI[3]. Figure 5 displays both series, the one from GSI and the one computed by c5++ in fully automated mode, including ambiguity resolution. Since the GSI time series contains not only INT2 results, but includes all kinds of Intensive sessions, only results for the INT2 type experiments can be compared against each other (Fig. 6). The mean difference between both solutions is less than 3 μsec, having a standard deviation of about 19 μsec. Note that the c5++ solution uses a different mapping function than the one applied in CALC/SOLVE and that the c5++ solution is free from any kind of constraints which is a possible explanation for the differences. Moreover, considering the choice of other models as described in Nothnagel and Schnell (2008), even very small differences between the two results might be explainable. Overall, it can be concluded that the fully automated c5++ processing scheme can provide real-time UT1 estimates at the same accuracy level as a state-of-the-art VLBI analysis package would provide if operated by an experienced analyst.

7. Conclusions

Fully automated processing and analysis of UT1 experiments has become reality. The VLBI module of c5++ has been adopted for this purpose by adding the functionality for automated ambiguity resolution which remained as one of the large hurdles for unattended operation since this processing step usually requires human interaction by the analyst. Because the results agree well with those obtained from another software package, c5++ automated UT1 processing can be applied for routine operations like the Intensive sessions. Although with the current choice of the functional model (see Section 4.1.1) ambiguities could be resolved for all INT2 sessions without human interaction, it is still possible that in a future data-set the algorithm will not converge. Thus, c5++ will be extended with functionality to try several other approaches for the ambiguity resolution step if the suggested algorithm does not converge after a user-defined number of iterations.

8. Outlook

Currently, the fully automated analysis scheme is tested with INT2 sessions on a semi-routine base. GSI used the c5++ solution to estimate UT1 directly after the correlation has finished and put the results on a FTP server. Additionally, the IERS has agreed to use this output in order to test their impact on the generation of daily UT1. Thus, if these new near-real time UT1 measurements are acceptable for the routine UT1 product, it is anticipated that GSI can provide their solutions based on automated processing with c5++. As suggested by Luzum and Nothnagel (2010) other Intensive sessions could also be automated, providing UT1 on a daily base in near-real time. The Intensive experiments operate with long East-West baselines that give high sensitivity for UT1 monitoring, but these sessions are insensitive to any of the wobble parameters. Adding a third station, that shares a North-South baseline with one of the two sites, as well as extending the length of the session by a few hours may give enough stability to decouple the three parameters and obtain a meaningful set of all three Earth orientation parameters. Extension of the INT2 experiments would either require a station in Southern Africa (for a NS baseline w.r.t. Wettzell) or using one of the Australian telescopes to obtain the North-South baseline with a Japanese antenna. The latter configuration would be preferable as most of the Australian VLBI sites are connected with optical fiber, which enables fast data streaming via international high-speed networks. Since for such a scenario three baselines need to be correlated, moderate upgrades at the correlation centers might be required, whereas hardly any modification in the post-processing chain are necessary. Given that such extended Intensive (eINT) experiments are operated similar to the recent ultra-rapid sessions, users would be provided with a complete and consistent set of all three Earth orientation parameters and the IERS would be able to improve their products. Moreover, experience gained from the automated processing of such session might be valuable for establishing the next generation VLBI network (VLBI2010) as described by Niell *et al.* (2007).

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