4-5 Real-time Determination of UT1 by Means of e-VLBI

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Very Long Baseline Interferometry allows to measure universal time UT1 directly among all space geodetic techniques.

In order to decrease the turn-around time of dedicated UT1 sessions an automated real-time processing chain has been set-up which provides real-time measurements of UT1. Within this paper, we are going to discuss the details of this processing chain, including the data-transfer over high-speed networks, called e-VLBI. Moreover, we demonstrate the effectiveness of an automated analysis algorithm, for completely unattended operation and provision of results.

Keywords
Very Long Baseline Interferometry, VLBI, Universal Time, UT1, Earth orientation parameters

1 Introduction

Nowadays Very Long Baseline Interferometry (VLBI) is the only space geodetic technique which allows a determination of all components of Earth rotation. Thereby, 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. Thereby 24-hour sessions, named R1 and R4, depending of the choice of participating stations, allow to derive all three Earth Orientation parameters, as well as enable users to estimate terrestrial and/or celestial reference frames, by accumulating many of these sessions over several years. In the recent years dedicated one-hour single baseline sessions, up to 7 times a week, have been established, with the goal to provide estimates of UT1 with a higher time resolution than the 24-hour experiments, which are only carried out twice a week. In order to accomplish such frequent experiments the work-load has been split into three distinct observing programs (see Fig. 1) which are named Intensive 1 (INT1), Intensive 2 (INT2) and Intensive 3 (INT3). Although the turn-around time of these experiments has been improved greatly, there are still bottlenecks in the processing chain which permit to access UT1 within a few minutes after the last scan has been observed. Although these dedicated sessions are designed to provide low latency UT1 results the output from these sessions reaches the IERS prediction center with delays of 1–3 days. Therefore, NICT has started a national and international collaboration to test and verify a completely unattended and automated VLBI processing system which allows to observe UT1 in real-time by taking advantage of modern high speed internet infrastructures.

2 Measuring UT1 by means of VLBI

2.1 Importance of VLBI for the determination of UT1

Earth orientation parameters (EOP) describe the rotatory position of the solid Earth relative to a space-fixed non-rotating referenc-

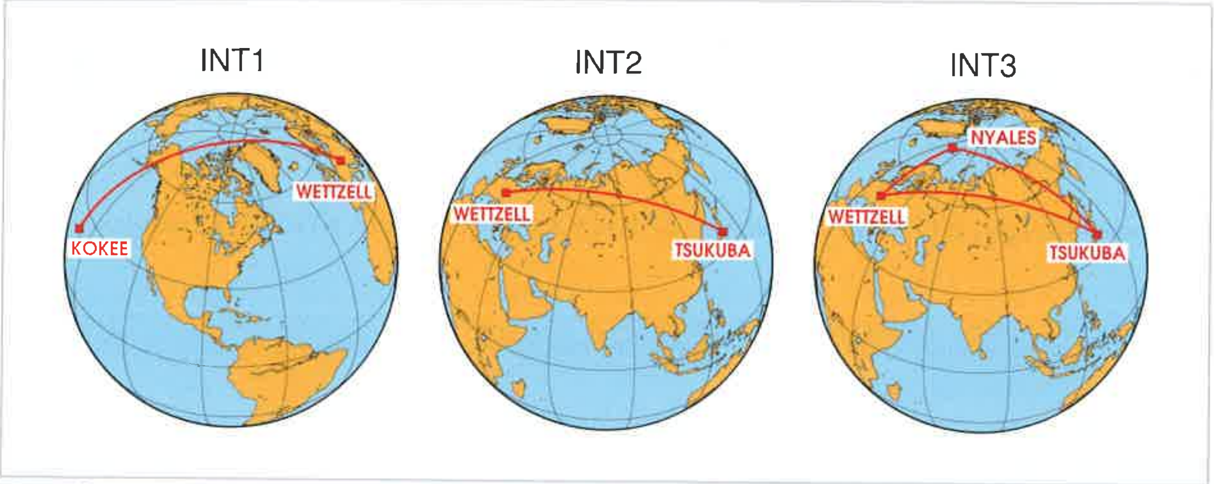

Fig.1 *Baselines of the three types of intensive experiments*

INT1 and INT2 are operated as single baseline sessions, whereas INT3 operates with three stations. The INT3 station network displayed here can vary from time to time, by replacing one or two sites with KOKEE or SVETLOE.

es system. Global Navigation Satellite Systems (GNSS) are capable to monitor two of the three EOP, i.e. the pole-coordinates Xp and Yp. Since VLBI is the only technique which is directly linking to the inertial celestial reference frame it is a crucial method for determination of UT1. The transformation between the celestial and the terrestrial references system is defined (IERS conventions)[1] to be

$$x_{TRF} = R_2\,(-Xp)\ *\ R_1(-Yp)\ *\ R_3(s)\ *\ R_3(\theta)\ *\ PN\ *\ x_{CRF} \qquad (1)$$

where s denotes the motion of the non rotating origin on the moving equator due to infinitesimal displacement of the celestial pole and PN represents the transformation matrix covering precession and nutation terms. The numerical link between theta and UT1 was determined to be

$$\theta=2\pi(0.779057273264 + 1.00273781191135448(UT1\text{-}UT10))\ \text{[rad]} \qquad (2)$$

Since radio source positions and station coordinates are known in advance and polar motion can be taken from predictions it is possible to determine UT1, even in real-time. VLBI observables (Fig. 2) only determine the baseline length between to ground-based radio telescopes. Thus, given that a sufficient number of observations is available it is possible to determine UT1 within a least-squares adjustment process, by separating nuissance parameters like troposphere and station clocks.

2.2 UT1 forecast and latency

Due to the fact that UT1 is a natural time scale which is directly linked to the Earth rotation it underlies different physical origins than UTC which can be seen a constant synthetic time-scale. Thus, UT1-UTC reflects all variations and irregularities of the Earth's rotation. Since the exact knowledge of UT1-UTC is of high importance for a variety of applications, such as the determination of satellite orbits, space craft navigation, spaceflight communication, astronomical and geophysical research and space geodetic applications like satellite gravity missions.

Due to the complexity of the Earth system there exist various components and interactions which are capable to induce variations of the Earth's rotation and the direction of the rotation axis. The main effects include Earth and ocean tides, interactions with the atmosphere, core-mantle interactions and other loading effects. The time-scale of such effects varies be-

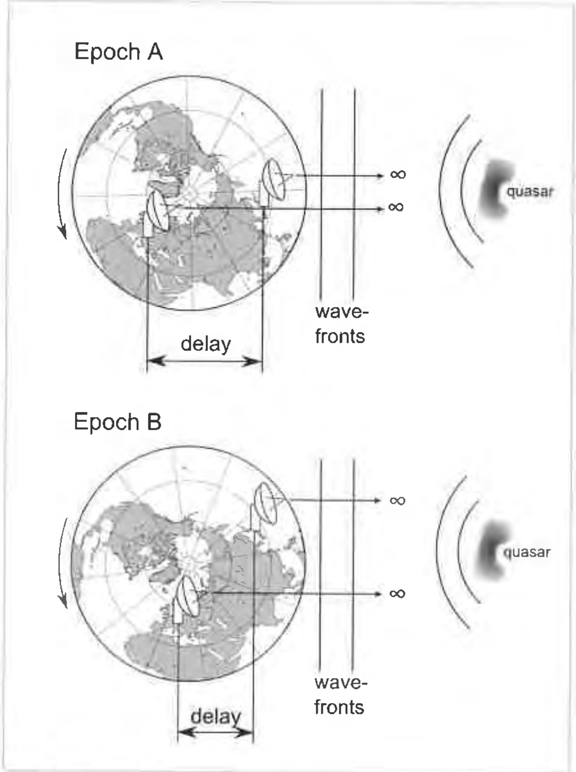

Fig.2 Basic principle of VLBI

Two or more radio telescopes are observing radio emissions from a far away quasi-stellar object (quasar). Cross-correlation of the obtained signals provides the time delay between a wavefront passes the first and second station. Delays are depending on the Earth's orientation in the celestial frame, the location of the VLBI antennas and the source position. Since the latter two are well known, one can estimate Earth orientation parameters, by observing a different radio sources over a certain time-span. It is obvious that longer East-West baselines have higher sensitivity for measuring changes in the Earth rotation phase (i.e. UT1-UTC), whereas North-South baselines don't provide valuable information to determine this parameter.

tween a few hours and tens of thousands of years and their impacts range from one to several thousand microseconds (Schuh et al., 2003)[2]. A large fraction of their variability can be described by means of geophysical models but a smaller but significant portion remains unpredictable.

For all time-critical applications mentioned before the IERS Rapid Service Predication Center provides official EOP values including UT1-UTC on a fast turn-around basis. Thereby predictions are necessary to cover the time after the last session was observed and to provide the users with meaningful values of the Earth's orientation. For such predictions all known variations and periodicities of UT1-UTC are taken into account, proper smoothing methods are applied and short-term meteorologic forecasts provide useful input for calculating the atmospheric angular momentum functions. Nevertheless, the accuracy of predicted UT1-UTC decreases when the time between the current epoch and the last observation gets longer as depicted in Fig. 3.

In order to improve that situation daily one-hourly intensive single baseline sessions (Fig. 1) were designed to monitor UT1-UTC with much lower latency which helps to strengthen the IERS forecast products. Nevertheless, due to bottlenecks in the processing chain results are usually available between 12 hours and 3 days after the last observation has been made. Thereby, in many cases processing is delayed by environmental factors like weekends, national holidays or availability of the analyst who computes the UT1-UTC solution and provides it to the IERS.

2.3 Measurement precision

According to Whitney et al (1976)[3] VLBI band-width synthesis measurement precision can be denoted by

$$\sigma_r = \frac{1}{2\pi \cdot SNR \cdot B_{eff}} \tag{3}$$

where B_{eff} is the effective band-width, determined by the way how the channels are spread over the whole observing band. Moreover, the signal to noise ratio (SNR) is defined to be

$$SNR = \rho\sqrt{BT} \tag{4}$$

Since B_{eff} can't be improved much and the correlation coefficient r is determined by the system characteristics and the strength of the selected radio source, the only way to improve

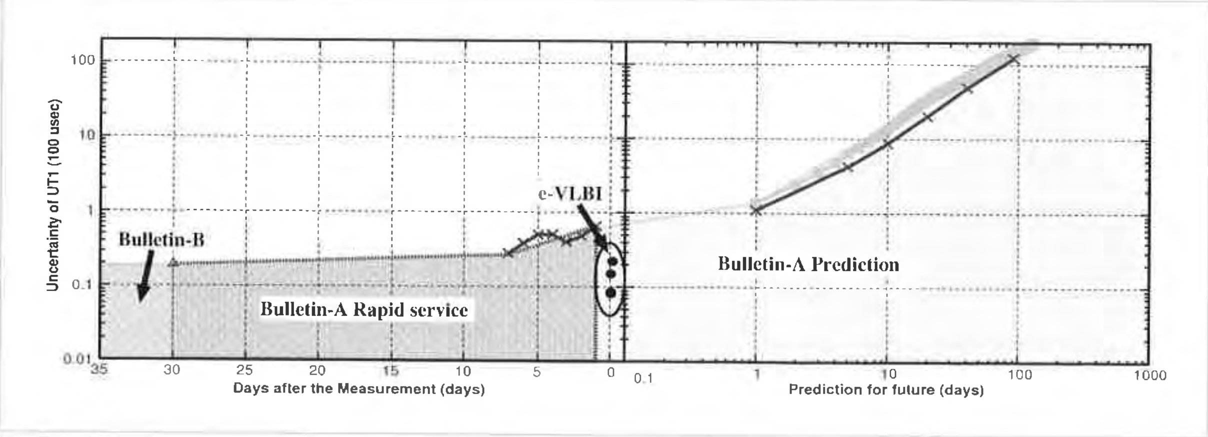

Fig.3 *Uncertainty of UT1 from the IERS bulletins*

The horizontal axis indicates the time before and after the present (after Sekido et al, 2008). It can be seen that predictions for the next day have an uncertainty of more than 100 μsec and forecasts for periods over 10 days exceed the millisecond level. Black dots represent the formal error of ultra-rapid e-VLBI experiments, being almost one order of magnitude better than the Bulletin A rapid service.

the precision of the observables is to increase either the observing channel bandwidth B or to lengthen the scan time T. Since the latter one goes along with a worsening of the observing geometry, only a broadening of the channel bandwidth appears as meaningful solution for improving the measurement precision, and thus obtaining more accurate estimates of UT1.

3 e-VLBI

3.1 e-VLBI technique

If the observing bandwidth increases, the data-rate at which raw observations are sent to the correlators, increases at the same ration. Thus highly accurate and low latent UT1 experiments are only achievable if sophisticated high-speed infrastructure connects the various components of VLBI. Based on the recent progress in network technology and network infrastructure, optically linked VLBI for real-time or near-real-time VLBI (Whitney, 2000)[4] has become feasible. This technology has been named e-VLBI and the number of radio telescopes with fiber connections has been continuously growing since 2000. One of the key factors to realize the rapid output of results is the choice of a sophisticated data transfer protocol. As discussed in the prior section, larger observing bandwidth, which increases the data-rate, improves the observation precision. For such observations data-rates of 256 Mbit per second (Mbps) or larger are usual dimensions which have to be transmitted over global networks. Thereby, the amount of data per station easily exceeds the Terrabyte range. Thus, high-speed data transport from the observation site to the correlation center is required at a rate which is at least as high as the data is sampled. TCP/IP is a protocol that guarantees reliable data-transport over the network and it is widely used for applications which require rigorous data-transfer. However, one drawback of TCP/IP is that it slows down the data transport when distances are getting longer. According to Hirabaru et al, 2004[5] one can find a theoretical limit of

$$rate[\mathrm{bps}] = \frac{8WS[\mathrm{byte}]}{RTT[\mathrm{sec}]} \qquad (5)$$

where WS is the window size and RTT denotes the round trip time between two ends of the network. This means that the transmission rate decreases inverse proportional to the RTT. Basically, this limitation comes from the acknowledgment mechanism inherent to TCP/IP, which ensures the rigorous and correct packet transport.

In order to overcome this limitation, a UDP/IP based high speed network file transfer protocol over long distances, named "Tsunami" was developed by the Advanced Network Management Laboratory of Indiana University (Meiss, 2004)[6]. Colleagues from US, Finland and NICT were the first who applied this protocol to stream data from the VLBI interface card through global networks. Thereby, data-rates of 600 Mbps and more over distances of several thousand kilometers could be achieved on a 1-Gbps network, which was only capable to provide 32 Mbps when data was sent via a standard TCP/IP protocol.

3.2 Automation

Data-transfer via high-speed internet connections and the usage of sophisticated transport protocols help to bring the observational data from the antennas to the correlation center, but as long as data had to be processed manually delays occurred frequently. Thus, it is important that automated scripts read the incoming data streams and feed them to the correct processing stages. As for international VLBI experiments it can happen that data format differ between VLBI observatories, which requires the correlation centers to carry out a format-conversion before the data can be fed to the correlators. NICT has developed (Sekido et al., 2008)[7] an automated processing chain which smoothly handles all the stages from the data-reception through the correlation process and the post-processing stages.

As depicted in Fig.4, data are handled in a distributed computing environment which allows to carry out several tasks in parallel, using multiple CPUs. Thereby, a server assigns incoming data to conversion clients and picks up the converted data-packets to be fed into the correlator. The correlator itself as also realized by distributed computing. In order to ensure that the automated processing chain does not fail during network outages or hardware crashes, software components were designed in a fashion which dynamically assigns available computing resources. A monitor client coordinates the correlating CPUs and allows the user to check the processing stage. Output from these correlators is accumulated and as soon as all channels from a scan have been correlated, band-width synthesis is applied and the geodetic observables, i.e. phases, amplitude, delay and delay rate are written to a dedicated format (named KOMB). From there on post-processing and space geodetic analysis of the results can start. Since the whole system is based on a distributed computing environment, the performance of the whole system can be improved by adding more CPU power or replacing older CPUs with modern hardware. Moreover, out-of-the-shelf hardware components can be used

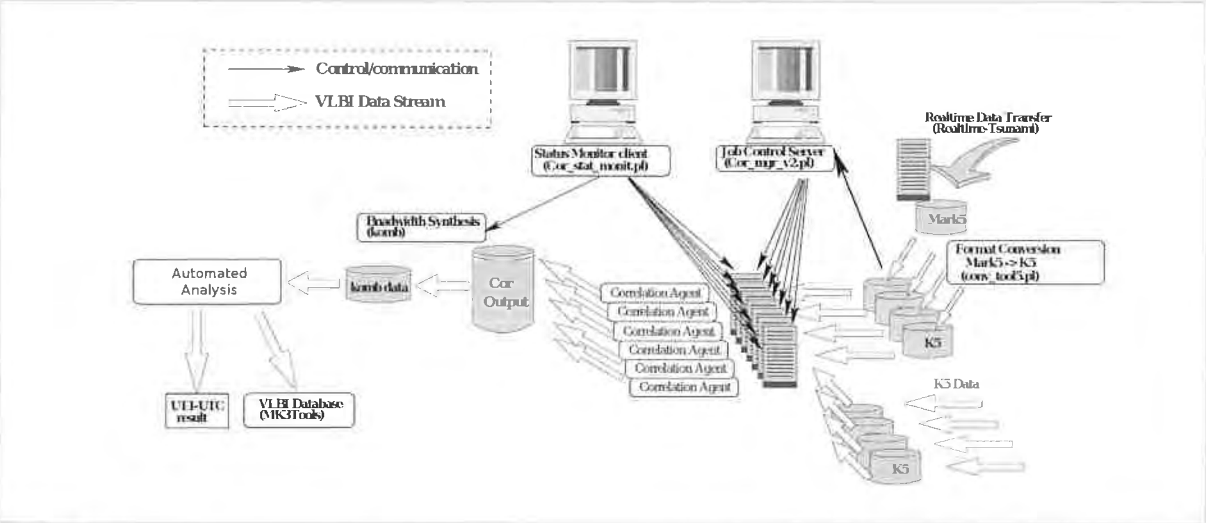

Fig.4 *Automatic data processing which takes advantage of a distributed computing environment*

The software correlator and data format converter are pipe-lined to ensure smooth processing the VLBI data.

for this systems, which reduces the initial and running cost and allows easy maintenance and upgrades.

3.3 Geodetic analysis

Once a sufficient number of scans have been correlated space geodetic analysis can be launched and first estimates of UT1 are obtained. With the advance of the processing, the number of usable scans will grow and the estimates of UT1 will get more reliable, respectively its formal error will get smaller.

3.4 Combining correlation output and external information

Although the output from the correlator provides the basic information for geodetic analysis, additional information is necessary to start with the final processing stage. Meteorologic data, i.e. pressure, temperature and humidity, as well as cable calibration information is extracted from the log files at each site and interpolated to the corresponding observation epochs. Moreover, a-priori information about the wobble parameters *Xp* and *Yp* is necessary to derive a meaningful values of UT1-UTC. As shown by Nothnagel and Schnell (2008)[8] also careful selection of nutation parameters is mandatory, in order not to bias the results. As for the selection of the wobble parameters, once can choice between the predictions from the IERS and those values based on ultra-rapid GPS products. Although the later once should be more reliable, they can be biased as well as they rely entirely on predictions of UT1. In order to overcome this problem, the best way would be an estimation of all three Earth orientation parameters by means of VLBI, as discussed in section ?

3.5 C5++

Driven by the need to have a flexible, robust and modern analysis software for rapid UT1 estimation Hobiger et al. (2010)[9] have developed a VLBI specific solution which fulfills all these requirements. Thereby, they authors took advantage from an existing software package, named CONCERTO, and designed the analysis software newly in C++, which led to the naming of C5++. This space geodetic software is not only dedicated to VLBI, but is also used for SLR and GPS analysis. Since all space-geodetic techniques can utilize the same physical and geophysical models from C5++, consistent combination across the techniques can be realized. Thereby, results can be either combined on the normal-equation level or on the observation level, in accordance with the goals of the Global Geodetic Observing System (GGOS). Since the correlator output format can be read directly with C5++, no intermediate interface is necessary. Moreover, ambiguity resolution and ionosphere correction can be done within the framework of C5++. Not only the target parameter, i.e. UT1, will be estimated with C5++ but also databases for the VLBI community are expected to be created with that software. As shown in Fig. 5, it is also possible to input a-priori delay models to the correlator in order to achieve highest possible

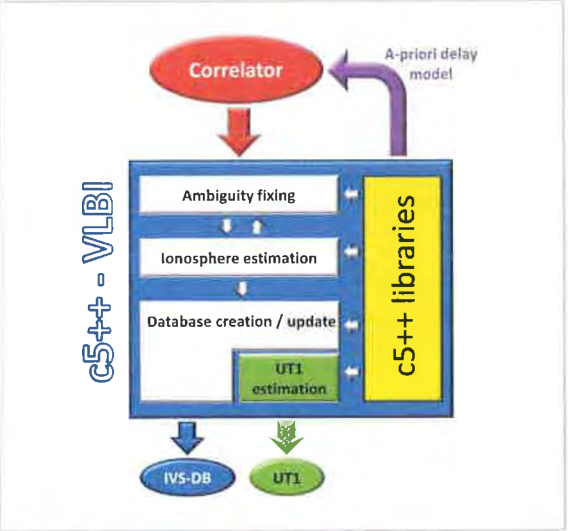

Fig.5 *Flow-chart of automated*

Analysis and UT1 estimation using the C5++ libraries. Other software packages currently require human interaction for ambiguity fixing which slows down the processing chain. The C5++ routines overcome this problem and fully automated processing becomes feasible. Beside the target parameter UT1-UTC, ambiguity free observations are written to a database, which can be used for other research purposes or rigorous re-analysis campaigns.

consistency between all the data processing stages.

Correctness of the software has been verified with the IVS software comparison compaign (Plank, 2010)[10] leading to differences of less than a picosecond when comparing theoretical delays with those of other VLBI analysis software packages.

4 Results

4.1 Setting a world record in the fastest determination of UT1

Based on the automated processing infrastructure (Fig. 6) developed by NICT, Matsuzaka et al. (2008) [11] report the world fastest determination of UT1, i.e. 3 min 45 seconds after the last scan has been observed. Similar near real-time results were achieved in the meantime and such outcomes have started to get the community interested in these short latency UT1 results. Other than the usual Intensive sessions, ultra-rapid intensive results are available up to 100 times earlier than current products, which makes its usage for a variety of applications feasible.

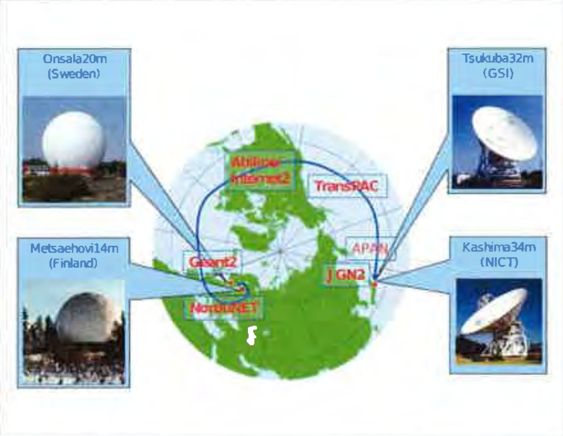

Fig.6 *VLBI stations participating in ultra-rapid UT1 experiments*

The experience gain from this dedicated sessions can be ported to the Intensive sessions (Fig. 1), when station have similar network connectivity as those use for the ultra-rapid experiments.

4.2 Operational product and implications

Based on the experience and the results gained over the last three years, the IERS has declared its interest in those ultra-rapid UT1-UTC results, in order to include this low latency information in its daily forecast of the Earth orientation parameters. First results were submitted in July 2010 and the IERS is currently evaluating these data, before including the results on a routine base. It is anticipated that the ultra-rapid results will help to minimize prediction errors of UT1-UTC and provide this essential parameters for a variety of applications. Not only real-time GPS will benefit from this achievement, but also space-craft navigation and deep-space communication will be provided with more accurate UT1 values.

Currently, only the German-Japanese baseline Wettzell-Tsukuba is capable to run the experiment in ultra-rapid mode. This is not only related to the internet connectivity at both sites, but also – to a large extent – provided by the automated processing tools created by NICT. Thus, it is anticipated that in the very near future the INT2 sessions on this baseline will provide their results in near real-time. Moreover, expensive night-shifts and manual interaction by technical operators have been reduced and/or made obsolete which helps to cut operational cost of this type of experiment. The other two intensive programs, could be equipped with similar tools, given that their internet connectivity permits to run the experiments in ultra-rapid mode.

5 Outlook

Once the ultra-rapid UT1 product has been established at the IERS, one can start aiming at the other Earth orientation parameters. Although the pole coordinates can be observed by GPS in near-real time, those parameters are implicitly depending on the UT1 estimates from VLBI. Thus, for an utmost consistent set of all three Earth orientation parameters, dedicated VLBI experiments are necessary. Other than the single baseline experiments for UT1, at least a three station network is required to decouple the pole coordinates and estimate the phase of the Earth rotation (UT1) at the same time. The intensive experiments operate with long East-West baselines which give high sensitivity for UT1 monitoring, but are completely insensitive to any of the wobble parameters. Adding a third station, which shares a North-South baseline with one of the two sites, should give already 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 is 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 as 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 prediction products.

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