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Universal Time from VLBI Intensives with Ray-traced Delays

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Abstract

VLBI Intensive sessions are used for the estimation of UT1–UTC (ΔUT1) which is needed in near-real-time for the accurate prediction of Universal Time (UT1) as well as for navigation purposes. These 1-hour IVS sessions (INT1 and INT2) are carried out every day to provide this quantity on a regular basis. Due to the small number of observables per session most parameters, which are usually estimated in VLBI analyses, are fixed to their a priori values. This means that all a priori values should be known as accurately as possible to derive the most accurate ΔUT1 estimates. One possibility of determining a priori tropospheric delays is ray-tracing through numerical weather models. These tropospheric delays also account for azimuthal asymmetries possibly also increasing the accuracy of the ΔUT1 estimates. We analyze Intensive sessions from July 2010 to October 2011 using the Vienna VLBI Software (VieVS) and compare the obtained ΔUT1 values based on ray-traced delays to those from standard approaches. Furthermore we calculate length-of-day (LOD) from ΔUT1 and compare these values to LOD from GPS.

1. Universal Time from VLBI

Earth Orientation Parameters (EOP) are required for positioning and navigation purposes on Earth and in space. Very long baseline interferometry (VLBI) is the primary space geodetic technique for the estimation of Universal Time, one of the five EOP. Global Navigation Satellite Systems (GNSS) are only capable of estimating short-term Universal Time changes because it is not possible to separate ΔUT1 from satellite orbit parameters on time scales longer than a few days.

1.1. VLBI Sessions

VLBI observations are usually separated into two different types of experiments. They differ in observation duration and in their purpose. There are the 24-hour sessions which are carried out two or three times per week. There are roughly six to ten telescopes participating in such a 24-hour session. The latency of those sessions is about two weeks because the recorded data at the station has to be transferred to the correlator, which is not always possible with a wired connection. The two-week delay is not a problem for the estimation of station coordinates, but Universal Time is needed in near-real time due to prediction purposes. Therefore the IVS observes shorter single-baseline sessions—the so-called Intensive sessions. Those last usually only one hour and have a latency of a few minutes to two days. Their primary goal is to estimate Universal Time.

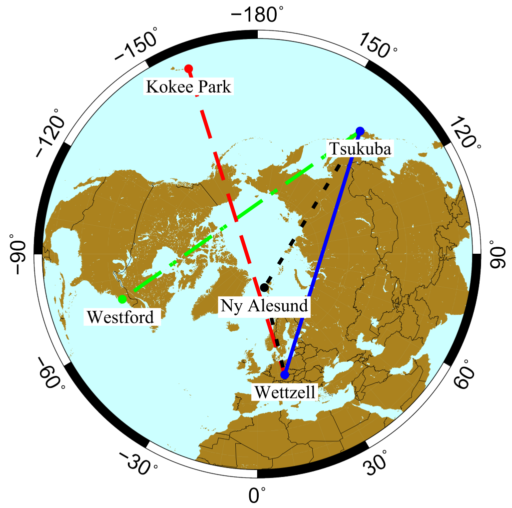

Figure 1. Intensive baselines on which Universal Time is observed.

1.2. Intensive Session Network

There are three types of Intensive sessions within the IVS. INT1 sessions (dashed line in Figure 1) are carried out on the baseline from Wettzell in Germany to Kokee Park in Hawaii. INT2 sessions (solid line) include Wettzell and Tsukuba in Japan; INT3 sessions (short-dashed line) again include Wettzell and Tsukuba and in addition Ny-Ålesund on Spitsbergen. In late 2010 there was another temporary baseline (dash-dotted line) to observe Universal Time: Westford replaced Wettzell in INT1 sessions because the German station was off for repair. The baselines observing Universal Time within the IVS are shown in Figure 1.

2. Ray-tracing

For the estimation of Universal Time a priori information about the tropospheric path delay is needed. A widely used approach to obtain the a priori delay is the formula by Saastamoinen (1972, [8]) as refined by Davis et al. (1985, [4]), which is used for determining the zenith delay from pressure measurements at the site. Together with a mapping function the slant delay can be calculated. A different approach is ray-tracing, which is described in detail by Nafisi et al. (2012, [6]). Based on meteorological parameters one can estimate the refractive index n at one point. The Eikonal equation in vector notation reads:

$$|\nabla L|^2 = n^2(\vec{r})$$

where ∇L are the components of the ray direction.

The Eikonal equation describes the propagating direction of an electromagnetic wave in a medium. From the Eikonal equation one can derive seven partial differential equations. Six of them must be solved simultaneously. From a known (curved) path together with known refractive index values along the path, we can calculate the tropospheric path delay a priori.

Table 1. Root mean square differences with respect to IERS finals and mean formal error of ΔUT1.

Tropospheric model	RMS w.r.t. IERS finals	Mean formal uncertainty
p_0 Saastamoinen/VMF1	17.8 μs	13.1 μs
ECMWF/VMF1	17.8 μs	13.0 μs
Ray-tracing	18.3 μs	13.0 μs

2.1. Vienna Ray-tracer

Our ray-tracing algorithm is written in Matlab which makes it rather slow compared to a compiled programming language. However, some simplifications can be made to improve the speed of the program. For example the assumption that the ray does not leave the plane of constant azimuth yields a “2D ray-tracer”.

We use operational analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) with a resolution of 0.5° in both latitude and longitude and 25 pressure levels in the vertical.

3. Analysis

We analyzed 355 sessions from 15 July 2010 to 26 October 2011 using the Vienna VLBI Software VieVS (Böhm et al., 2012, [2]). We took a priori station coordinates from the VTRF2008 (Böckmann et al., 2010, [1]) but changed the Tsukuba coordinates because of the Tōhoku Earthquake on 11 March 2011. The source coordinates were fixed to the ICRF2 (Fey et al., 2009, [5]). IERS EOP daily rapid data (finals) nutation offsets and polar motion were used, and we added high frequency EOP values as recommended in the IERS Conventions 2010 (Petit and Luzum, 2010, [7]). We considered values $> \pm 50$ μs and those with a formal error > 100 μs as outliers. We estimated a linear clock function between the stations and one zenith wet delay per station. As partial derivative for its estimation we used the corresponding mapping function — the wet VMF1 [3] and the calculated wet mapping function from the ray-tracer, respectively. For each session we estimated one UT1 value.

In order to compare our ray-tracing algorithm to standard approaches, we analyzed all Intensive sessions with three models for the a priori tropospheric delay: (1) the formula from Saastamoinen with pressure measurement at the site to get the hydrostatic zenith delay plus the hydrostatic VMF1, (2) a model based on numerical weather model data (ECMWF) and the VMF1 (hydrostatic and wet), and (3) ray-tracing. We have to mention that due to lack of NWM data we applied ray-traced delays only for stations Wettzell and Tsukuba. All other stations use model 2.

4. Results

Figure 2 shows the estimated ΔUT1 values w.r.t. the IERS EOP finals. There are small differences between the different models although most of the values do not differ significantly. Table 1 shows the RMS values of ΔUT1 values w.r.t. the IERS finals. The results from ray-tracing differ more than the other two models w.r.t. IERS finals. On the other hand, the mean formal uncertainty is of similar size. The difference in RMS could arise because the IERS finals

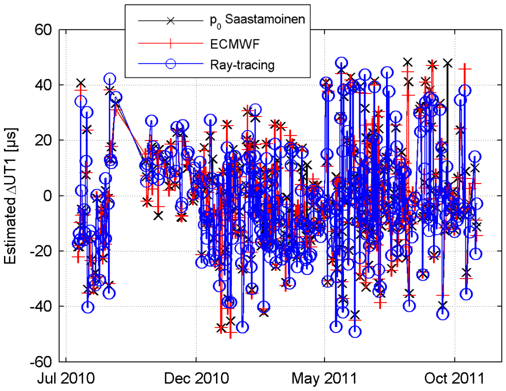

Figure 2. ΔUT1 estimates w.r.t. IERS EOP daily rapid data.

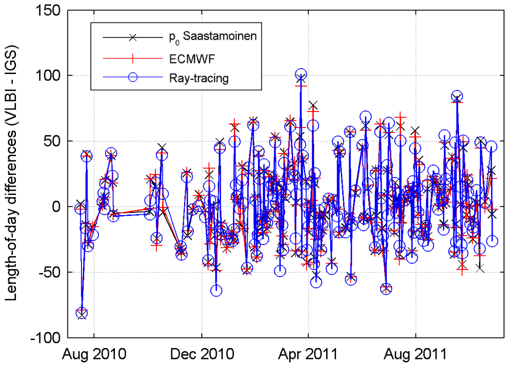

Figure 3. Length-of-day differences from VLBI and GPS.

were obtained based on results determined with the mapping function approach. As an external validation we converted ΔUT1 to length-of-day (LOD) and compared them to GNSS derived LOD values from the International GNSS Service (IGS). The differences of LOD values w.r.t. LOD from GPS are shown in Figure 3. If we separate the derived values according to the type of Intensive session, we find statistics as shown in Table 2. We can see that there is an improvement with ray-tracing for INT2 and INT3 as well as for the baseline Tsukuba–Westford. Only for the INT1 sessions the RMS is not improved. From the overall accuracy (column 'all' in Table 2) it seems that there is no benefit from using ray-traced delays. However, there are more INT1 sessions (251) than other sessions (104), for which ray-tracing does improve the estimated ΔUT1 values.

5. Conclusions

We used ray-tracing for calculating a priori tropospheric delays for VLBI Intensive sessions. We compared those with standard mapping function approaches. As an external validation we converted the estimated ΔUT1 values to length-of-day to carry out a comparison to GPS-derived LOD. Although the overall accuracy seems to be unchanged, it is worth having a closer look at the four different baselines. Ray-tracing does improve the accuracy for INT2 and INT3 sessions

Table 2. Root mean square of LOD differences from VLBI and GPS treated separately for the different Intensive sessions.

Tropospheric model	RMS LOD w.r.t. IGS-LOD [μs]			
	INT1	INT2/3	Ts–Wf	all
p_0 Saastamoinen/VMF1	30.8	27.1	24.6	29.8
ECMWF/VMF1	30.4	26.1	25.1	29.3
Ray-tracing	30.8	25.3	23.5	29.5

as well as for the temporary Tsukuba–Westford baseline by more than 1 μs. INT1 sessions, which are the majority of the experiments, however, show no improvement when using ray-traced delays.

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