Task Force on IVS Intensives

Updated Final Report

Rüdiger Haas – for the Task Force on IVS Intensives

Abstract In 2010, the IVS set up a task force to study the Intensive sessions with the goal of evaluating the Intensives and suggesting ways to improve them. The task force presented its final report to the IVS Directing Board in May 2017. This report consisted of a review of recent IVS Intensive research and recommendations for future improvement of the Intensives. The report is now being presented to the IVS in general as a special report in the 2015+2016 Biennial Report. At the same time, the opportunity was taken to update the report with the addition of information about VGOS INT01 preparations, new information about source constellation influence (spatial sky coverage) and temporal coverage, and related references. It should be noted that the reporting of research efforts within the IVS community is not exhaustive; instead major trends are covered.

1 Introduction

At its 23rd Directing Board (DB) meeting, held on 12 February 2010 at the University of Tasmania in Hobart, the IVS DB created the *Task Force on IVS Intensives*. The initial members of this task force were Rüdiger Haas (chair), Axel Nothnagel, Kerry Kingham, Brian Luzum, Dirk Behrend, Shinobu Kurihara, Thomas Hobiger, Minttu Uunila, and Zinovy Malkin. During later years, some of the members left the task force because of retirement or change of job.

The initial idea of the task force was to study various aspects of the Intensive (INT) sessions, with the overriding goal of improving the INT results. The objective of the INT sessions is to provide highly accurate and low latency UT1 results. However, the problem is that the INT sessions still do not live up to these expectations and unfortunately do not provide the expected precision and accuracy of UT1, and that the latency still could be improved. For example, Baver et al. (2012) reported RMS differences w.r.t. the IERS C04 series on the order of 25 μs for INT1 in 2011. Malkin (2013) gave RMS values w.r.t. IERS C04 of 18.0, 9.9 and 18.5 μs for INT1 (2005–2011), INT2 (2005–2011), and INT3 (2007–2011), respectively. In contrast to this, IVS network sessions provide RMS values that are better than the INTs by a factor of 3 to 4.

Topics of the task force were to study potential ways to improve the INT results. A proposal for a unified analysis strategy for INT should be developed, including a strategy for three levels of INT products. The three level INT products were meant to be based on the latency of the UT1 results, i.e., Ultra-rapid UT1, rapid UT1, and final UT1.

Numerous studies concerning the INTs were performed during the past years in the IVS community. The efforts can be separated into two main categories. The first category covers scheduling and operations of INT sessions, while the second category covers modeling and analysis. This report covers major trends, instead of providing an exhaustive description of all research efforts within the community. For brevity, the bibliography only lists an author or group's latest pa-

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per about a research activity, except where an earlier paper is useful to support the discussion of the activity.

2 Scheduling and operational aspects

2.1 Source constellation influence (spatial sky coverage)

Baver et al. (2004) noted a link between better sky coverage and lower UT1 formal errors. Gipson and Baver (2016a) reported the expansion of the INT01 scheduling source list from ∼30 strong but unevenly distributed sources to all geodetic sources that are mutually visible at Kokee Park and Wettzell. This “maximal source strategy” was first tested in ten 2009 and 2010 IVS R&Ds, and it was adopted for all INT01 scheduling in summer 2016.

But using all mutually visible sources weakens the source set, so Baver and Gipson (2014) studied source sets with intermediate numbers of sources to balance source strength and sky coverage. They are testing a balanced source set in six 2016 and 2017 IVS R&Ds.

Other studies examined the areas of the sky that affect the UT1 formal error with more precision. Uunila et al. (2013) divided the area of mutual visibility between Wettzell and Kokee Park into six sections and analyzed INT sessions. They revealed that coverage of the corners of the mutual visibility area is important for obtaining small UT1 formal errors. Gipson and Baver (2015) used a minimization algorithm to determine the ideal distribution of observations. Their best case indicated that UT1 formal errors are minimized when observations are only made within each mutual visibility corner.

2.2 Observation order (temporal sky coverage)

Temporal coverage is the degree of repeated observing in areas of the sky throughout a schedule due to observation order. Baver et al. (2012) examined observed INT01 sessions and reported that good temporal coverage, especially near the centers of Kokee Park’s and Wettzell’s northeast and northwest quadrants, reduces sensitivity to atmospheric turbulence (the RMS about the mean of the UT1 estimates from a series of solutions into which random noise is introduced). Baver and Gipson (2013) used schedule simulations to show that atmospheric turbulence sensitivity is reduced by cycling evenly through observations in Kokee Park’s and Wettzell’s northeast quadrant, northwest quadrant and center (near azimuth 0°), instead of observing for a while in first one of these areas, then a second area, and finally the third area. The even cycling also reduced the unscaled UT1 formal error of a representative schedule from 23.5 μs to 10.3 μs.

2.3 Impact factor analysis

Leek et al. (2015) studied the use of so-called “impact factors” (IF) to identify the most influential observations to optimize the determination of the target parameters of a geodetic VLBI session. They show that the IF-strategy is superior to standard scheduling for INTs during 2009 through 2013. The IF-strategy is also applicable to schedule networks with twin telescopes. Networks with twin telescopes instead of single telescopes proved to lead to an improvement of about 50% in the formal errors of UT1.

2.4 Tag-along stations in INTs

Kareinen et al. (2017) showed that the inclusion of a third station in tag-along mode has the potential to improve the INT1 and INT2 results by up to 33%. This study was based on a complete year of INT1 and INT2 schedules and used full end-to-end simulations with a realistic error model including station specific atmospheric turbulence.

2.5 Dedicated ultra-rapid sessions

The goal to achieve UT1 with low latency was already addressed in 2007 in a Japanese-European collaboration. Periodically, dedicated INT sessions were scheduled and the observational data sent electronically to the Tsukuba correlator, where the data were correlated and analyzed and near real-time UT1 was derived, see Sekido et al. (2008). Very low latency was achieved (Matsuzaka et al., 2008) with results on the same accuracy level as the standard INT sessions (Haas et al., 2010; Koyama et al., 2010). As a result, the ultra-rapid strategy was adopted in 2009 for the regular VLBI intensive series INT2, which in turn led to improved UT1 predictions (Luzum and Nothnagel, 2010).

2.6 Ultra-rapid UT1 during normal 24-h IVS sessions

Matsusaka et al. (2010) showed that it also is possible to determine ultra-rapid UT1 results during ongoing standard 24-h long IVS sessions. Standard IVS sessions that included Onsala and Tsukuba (e.g., R1, R&D) were used and the observational data from Onsala were e-transferred in real-time to Tsukuba, where the data were correlated and analyzed, providing UT1 results already during the ongoing IVS session. However, since the 24-h IVS schedules are optimized for network observations and not for UT1 determination on just one baseline, a special analysis strategy had to be developed. Sliding-window approaches were applied using either a fixed number of observations (e.g., 35) or a fixed time interval (e.g., 3-h) with delay observations for the analysis. This strategy was then also applied to the two continuous VLBI campaigns CONT11 an CONT14. Haas et al. (2017) showed that the accuracies from the CONT ultra-rapid single baseline operations are roughly a factor of three worse than the results from both dedicated one-baseline sessions and/or the complete analysis of network sessions.

2.7 INT sessions with 2-h duration observations

Artz et al. (2012) investigated the impact of observation time on the results from INT sessions. A series of R&D INT sessions with 2-hour duration showed that the formal errors of UT1 decreased by a factor of $\sqrt{2}$, when compared to INTs with 1-hour duration, and that the agreement w.r.t. UT1 results from 24-h sessions improved by about 15%.

2.8 VGOS INT01 scheduling

Baver and Gipson (2017) used simulations to examine source catalogs and *Sked* file parameters in order to develop a proposed VGOS INT01 schedule file configuration. The configuration reduced the average UT1 formal error from 7.7 μs to 3.4 μs. But the configuration should be retested once the Kokee 12-m antenna's horizon mask is finalized.

3 Modeling and analysis aspects

3.1 Impact of ocean loading

The general importance of ocean loading on the determination of earth rotation derived from VLBI was shown by Scherneck and Haas (1999). For network sessions, impacts of up to 3 μs on UT1 were detected when testing different ocean loading models. It can be assumed that INT sessions with just 2 or 3 stations are affected in a similar way.

3.2 Impact of atmospheric loading

Uunila et al. (2012) tested using atmospheric loading for the analysis of INT sessions. However, they investigated this in connection to testing different mapping functions. They could not detect any significant difference larger than 0.01 μs on UT1 and could not identify whether this was due to the mapping function or the atmospheric loading.

3.3 Impact of seasonal station motion

Malkin (2013) investigated the impact of seasonal station motions on UT1 estimates from INT sessions. It was found that neglecting seasonal station motion affects, e.g., the INT1 series by more than 1 μs.

3.4 Impact of mapping functions

Kareinen et al. (2015) investigated the impact of mapping functions on the INT results. They tested the Global Mapping functions (GMF) versus the Vienna Mapping Functions (VMF1) and could not detect any significant difference larger than 1 μs on the accuracy of UT1.

3.5 Impact of a priori zenith troposphere delays

Teke et al. (2015) used zenith troposphere delays from GNSS processing and introduced these in the analysis of INT sessions. They did not find any significant impact on the corresponding UT1 results.

3.6 Impact of a priori gradient modeling

Böhm et al. (2010) used external gradient information based on raytracing for the analysis of INT2 sessions. They found changes of the estimated UT1 values on the order of 10 μs.

Teke et al. (2015) used horizontal total gradients estimated from GNSS observations and used these as a priori values for the analysis of several years of INT sessions. They converted the UT1 results to LOD and compared these to GNSS results for LOD. A slight improvement of agreement on the order of 1 μs was found for INT1 and INT2.

Gipson and Baver (2016b) used a priori gradient information based on the analysis of R1 and R4 sessions and applied it to the analysis of INT01 sessions. They found changes of UT1 estimates about 7.5 μs and a slight improvement on the order of less than 1 μs when compared to results from 24-h sessions.

3.7 Impact of raytraced a priori delays

Madzak et al. (2012) used raytraced delays as a priori values for the data analysis of INT sessions and converted the derived UT1 values to LOD. They found that the agreement of INT2 and INT3 sessions improved by more than 1 μs while there was no effect, neither positive nor negative, on the INT1 sessions.

3.8 Impact of locally measured pressure and cable calibration data

Kareinen et al. (2015) investigated the impact of local station data, i.e., locally measured atmospheric pressure and cable calibration data, on the accuracy of UT1 from INT sessions. They found an insignificant effect of less than 0.01 μs whether using locally measured data, or not. This required of course that the cable data were reliable and free of outliers.

3.9 Impact of a priori polar motion and UT1

Nothnagel and Schnell (2008) investigated the impact of a priori polar motion (and nutation) on UT1 derived from INT sessions from a theoretical point of view. They found a directly proportional effect with maximum values of up to 30 μs per milliarcsecond offset in polar motion (or nutation). This highlights the importance of accurate a priori polar motion.

Nilsson et al. (2015) used a Kalman Filter approach to make use of external information of polar motion and LOD from GNSS provided as IGS rapid products in the analysis of five years of INT sessions. They found a significant reduction of the WRMS differences w.r.t. UT1 results derived from IVS 24-h sessions, both from using polar motion and/or LOD separately. The largest reduction was achieved when using both polar motion and LOD.

Kareinen et al. (2015) investigated the impact of a priori polar motion values used in the analysis of INT sessions on the accuracy of the derived UT1 results. They found that the a priori polar motion data must not be older than 12 hours to achieve UT1 accuracy of better than 20 μs. To guarantee less than 5% degradation for the UT1 accuracy, the a priori polar motion must not be older than 6 hours.

3.10 Impact of a priori nutation

As mentioned earlier, Nothnagel and Schnell (2008) investigated the impact of a priori nutation (and polar motion) on UT1 derived from INT sessions from a theoretical point of view. They found a directly proportional effect with maximum values of up to 30 μs per milliarcsecond offset in nutation (and polar motion), which is significant since even state-of-the-art nutation models show deviations of as much as one milliarcsecond.

3.11 Impact of free core nutation

Malkin (2011) studied the impact of celestial pole offsets (CPO) on the accuracy of UT1 estimates. The CPO are corrections to the IAU 2000/2006 models for precession and nutation and are attributed to errors in precession and/or very low frequency nutation terms, as well as the free core nutation (FCN). There are only empirically determined models of CPO. Using these models in the analysis of INT sessions has an impact on the order of 1.4 μs.

Gipson and Baver (2016b) studied this effect further and found an impact of less than 1 μs.

3.12 Automated analysis of INT sessions

A fully automated way to analyse INT sessions was developed by Kareinen et al. (2015). It starts with the version-1 databases in S- and X-band and works completely automatically without any human interaction. Ambiguity resolution and ionospheric calibration are included in this analysis.

3.13 Robust estimators for the analysis of INT sessions

Kareinen et al. (2016) implemented an algorithm to automatically resolve the ambiguities in geodetic VLBI data using robust estimation with the L1-norm. The results of this study show that the L1-norm is better at automatically resolving the ambiguities than the L2-norm. The increase in the number of successfully analyzed INT sessions was 5% when using L1-norm instead of L2-norm, accompanied by smaller post-fit residuals in the final UT1 estimation step.

4 Recommendations

The conclusions from the studies in the IVS community concerning the INTs cover three main aspects, which are 1) scheduling, 2) a unified modeling and analysis strategy, and 3) INT products with three levels of latency and accuracy.

4.1 Scheduling

We encourage to continue studies concerning optimized scheduling of INT sessions. There are a number of promising approaches, e.g., impact factors and maximal source strategy, but also adding further stations to the INTs, which might lead to improved accuracy. However, with the upcoming VGOS network and corresponding operations, one general question is whether INTs in their current form will continue to exist in the near future at all (Nothnagel et al., 2016).

4.2 Unified modeling and analysis strategy

As a unified modeling and analysis strategy for INT sessions we propose to model all known effects that have been shown to significantly impact the accuracy of INT results. This will also be of importance for future VGOS observations. We propose to:

1. use the most recent reference frames, i.e. currently ICRF2 and ITRF2014, including seasonal station modeling.
2. use the most recent IAU models for precession and nutation.
3. use empirical FCN models.
4. use recent mapping functions (MF), however adapted to the different INT products (see next sub-section) according to the availability of the MF information. For example, GMF(GPT2) should

be for near real-time analyses, but VMF1 for post-processing, final INT analyses.
5. use a priori gradients, however adapted to the different INT products (see next sub-section) according to the availability of the gradient information. For example, gradients from numerical weather model (NWM) predictions should be used for near real-time analyses, while gradients from GNSS analyses and/or post-processed final NWM should be used for post-processing, final INT analyses.
6. use the most recent ocean loading modeling.
7. use atmospheric loading.
8. use cable-calibration data, at least for post-processing analyses.

4.3 Three-level INT products

We propose to strive for INT products on three levels, mainly distinguished by their latency and accuracy. These can be classified as products from “ultra-rapid”, “rapid” and “final” analyses. This fits also into the strategic plan of the IVS for the VGOS era (Nothnagel et al., 2016).

4.3.1 Ultra-rapid analysis

This INT product should make use of real-time data streaming, near real-time correlation, and near real-time automated data analysis (no human interaction), in order to achieve the lowest possible latency. The goal is to achieve a latency below 1-hour after the INT session. One dedicated IVS analysis center (AC) could have the responsibility for these products. However, higher robustness would of course be achieved with several ACs taking care of this. The results should be delivered as eopi-files to the IVS and IERS.

4.3.2 Rapid analysis

The rapid analysis can be performed based on the data bases produced in ultra-rapid mode. However, there should be human interaction to check the processing and guarantee quality of the results. This work could be done by one AC only and eopi-files could be delivered to the IVS and IERS with low latency, i.e. within 3 hours after the INT session. However, higher robustness would of course be achieved with several ACs taking care of this.

4.3.3 Final analysis

The final analysis should be based on a combination of unconstrained normal equations from several ACs via SINEX files. It was shown by Böckmann et al. (2010) that such an approach is suitable for the combination of analyses performed by several ACs and leads to better accuracy than each of the individual solutions itself. The latency of this INT product is expected to be lower, e.g., within one week after the INT session.

In any case, all analyses included in the three levels of INT processing should follow a unified analysis strategy, see the previous sub-section.

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