

Progress in Carrier Phase Time Transfer

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ABSTRACT

The progress of the joint Pilot Project for time transfer, formed by the International GPS Service (IGS) and the Bureau International des Poids et Mesures (BIPM), was recently reviewed. Three notable milestones were set. 1) The IGS will implement, at least in a test mode, an internally realized time scale based on an integration of combined frequency standards within the IGS network. This will eventually become the reference time scale for all IGS clock products (instead of the current GPS broadcast time). 2) A new procedure for combined receiver and satellite clock products will be implemented officially in November 2000. Receiver clocks are an entirely new product of the IGS. 3) The BIPM will coordinate an effort to calibrate all Ashtech Z12-T (and possibly other) receivers suitable for time transfer applications, either differentially or absolutely. Progress reports will be presented publicly in the spring 2001.

INTRODUCTION

In early 1998, the IGS and the BIPM formed a joint Pilot Project to study accurate time and

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frequency comparisons using GPS phase and code measurements (Ray, 1999). The IGS Analysis Center Workshop 2000, held in Washington, DC, during 25-26 September 2000, provided an opportunity to evaluate the progress of this project and to set updated objectives.

GPS INSTALLATIONS AT TIMING LABS

All timing labs are encouraged to install suitable dual-frequency geodetic receivers and integrate these into the IGS network (CCTF, 1999). About 14 labs currently do so, with additional sites under active development.

New hardware configurations

For time transfer, delay instabilities in the instrumentation are the main limitation in the long term, thus hardware configurations are of great importance. A number of suitable receivers, antennas, and cable types are currently available, but it is desirable to investigate new models as they are developed to ensure that improved hardware can be used by the community.

Relatively recent innovations that have been investigated include the 3S Navigation TSA100 temperature stabilized antenna for use with carrier phase GPS (Petit et al., 1998) and the Javad Legacy receiver. The TSA-100 antenna has also had its phase centers characterized (thanks to the U.S. National Geodetic Survey). The Javad's delay stability needs to be investigated and reported, for both the short- and long-term. The BIPM and several timing laboratories are in the process of commissioning Javad Legacy receivers, so results may be anticipated soon.

Further work is encouraged for the timing receivers that do not accept a synchronizing 1 pps input (e.g., AOA TurboRogue, Javad Legacy) to make them easier to run productively and to give better continuity across power cycles. Currently, the Ashtech Z12-T is the only suitable model, but further studies of it would be useful.

Timing labs contributing to TAI currently require receivers capable of producing the BIPM common view schedule. There are currently no IGS-compliant receivers which do this, thus requiring the lab to have two sets of equipment. Software is under development (P.Defraigne, workshop presentation) which will permit such an output to be produced.

Geodetic control

The needs of the geodetic and timing communities are partly different. Position stability is of critical importance for geodesists, whereas (once 20mm-level stability has been achieved) short antenna cable lengths are often more important to the timing community. This is because temperature effects average out for the position solution, but not for the time solution.

Practically, this means geodesists will mount their antenna as far from the receiver as required in order to achieve the best available stability at that site (limited by cable loss), whereas timing labs may want to mount their antennas on rooftops adjoining the laboratory holding the receiver, and accept the consequent loss of position stability and increased multipath.

It is important that the consequences for the IGS be acceptable — that the stations' contributions to the IGS efforts collectively are worth the required compromises. This is implicit in the acceptance of new timing lab installations. The position stabilities should be monitored to ensure the data are adequate for use by the geodetic community. Establishment of a local geodetic control network (one or more reference markers) near the main monument would ensure the long-term stability of the site and provide possibilities to investigate effects, e.g., caused by changes of equipment or the electro-magnetic environment at the site. If it is found that position stabilities are not adequate, then it may be useful to consult others who have successfully or unsuccessfully tackled the problem of rooftop mounts so that experiences may be shared.

Environmental stability control

Extensive work has been conducted showing the detrimental effects of temperature variations on receivers, antennas, and antenna cables (Overney et al., 1997; Petit et al., 1998; Bruyninx and Defraigne, 1999; Powers, 1999), and the improvements possible through temperature control of hardware and use of low-temperature-coefficient cables. The work of Weiss et al. (1999) on cables also proposed a more radical solution to reduce the influence of internal reflections using impedance matching and attenuation. These works are of crucial importance since delay instabilities in the instrumentation are the main limitation for time transfer, and it is believed that these are largely due to temperature effects (particularly of outdoor components).

The optimal trade-offs could be investigated between placing more hardware outdoors, cable lengths, trying more radical solutions (e.g., impedance matching), cable attenuation, cable type, and availability and ease of use of the consequent hardware. Further investigation of different cable types to find other suitable ones with low temperature coefficients would be useful.

Work has not been conducted to the same extent for environmental effects other than temperature, such as humidity, electromagnetic-fields near the receiver, EM-interference at the antenna, etc. While the extent of some of these effects may be estimated, further work is recommended to ensure that their significance has not been underestimated, and at least to record the conditions experienced by existing stations, which may provide a useful basis for comparison, and guidance in the future.

Multipath mitigation

Near-field multipath or scattering (see, e.g., Elosegui et al., 1995 and Jaldehag et al., 1996) can influence the antenna phase characteristics. This means that an antenna with known phase center calibration values may respond with significantly different characteristics if attached to, e.g., another metallic surface. Multipath effects are also relevant because they distort the search space during integer ambiguity resolution. The severity may be monitored by measuring code-phase, or code-clock differences, and this would allow an assessment of its significance for a given station, compared to that of environmental effects, allowing effort to be concentrated accordingly. For time transfer, the environmental effects are normally dominant.

Mitigation is possible using improved receiver technology, improved antenna technology, by repositioning the antenna (if it is a multiple of a carrier wavelength from a reflecting surface), or by resiting the antenna significantly further from any nearby obstacles and reflecting surfaces.

Integration with IGS network

The main barriers to complying with IGS standards at timing labs are resource constraints and a lack of expertise with geodetic techniques in general. This is particularly clear in the case of monumentation - timing labs may lack the expertise that allows them to decide on an antenna monument and mount, or to have any strong concept of the general standards expected for these. The assistance offered by the IGS Central Bureau helps in several regards - by offering advice; suggesting experts to contact; and displaying example station sites and monuments on the IGS web site.

Establishing and maintaining data flows is not a significantly different problem for timing labs than it is for geodesists in terms of the RINEX observation data. However time labs require additional types of data compared to the geodesists, such as the timing delays for the links between components and logs of discontinuities and other such events. To ease the operational burdens on individual timing laboratories, one or more Operational Data Centers for the geodetic receivers at timing labs should be considered. Such an Operational Center could serve as a helpful interface between the IGS and the timing labs.

DATA ANALYSIS

Accuracy and precision of clock estimates

The "absolute" accuracy of GPS-based clock estimates (modulo the calibration bias) is determined by the pseudorange data entirely. When analyzing 24-hour arcs of global data sampled at 5-minute intervals, the formal error estimates for the clocks are typically about 125 ps, assuming each pseudorange observation has an uncertainty of 1 m. An internal test of the true measurement accuracy can be made by comparing clock estimates at the boundaries between analysis arcs for receivers equipped with very stable oscillators. Doing so for a large number of days and receivers, we observe day-boundary discontinuities are not smaller than about 400 ps (RMS) and are usually in the 600 ps range (based on results posted at the USNO clock web site, <http://maia.usno.navy.mil/gpsclocks/index.html>). In some cases much larger excursions are seen and the overall performance seems to be site-dependent. The simplest resolution of the mismatch between formal errors and actual errors would be to revise the pseudorange noise figure from 1 m to roughly 3 m. It is widely assumed that the pseudorange noise is dominated by the effects of multipath, since the thermal noise figure is at the few-cm level, but quantitative studies of the effects of pseudorange multipath on clock estimates are lacking. Other effects, such as temperature sensitivity and inter-observable biases (see below), can also be important, particularly if neglected.

Using more pseudorange data (higher sampling rate and/or longer arcs) is expected to improve the clock accuracy. Higher sampling rates will only be effective as long as the dominant

multipath wavelength is shorter than the sampling period (if multipath is indeed the dominant error); otherwise the clock errors will not average down with the addition of more data. As shown by Senior et al. (2000) for the clock formal uncertainties, longer analysis arcs should average down the error effects, although less effectively than \sqrt{N} . Arc-boundary discontinuities seem to support this idea. The USNO analysis of 1-day arcs for the AMC2-USNO baseline shows discontinuities of about 523 ps RMS (after some editing of outliers). For the same baseline, an independent analysis by Larson et al. (2000) using 4-day arcs found discontinuities of 222 ps RMS. The apparent improvement by greater than $\sqrt{4}$ is probably not valid since somewhat different data sets and analysis strategies were used, but it does support the expectation that longer arcs can give more accurate clock results.

It has not been determined whether longer arcs differ only by a net clock bias or whether the frequency content is also changed (improved). If longer arcs provide better clock accuracy only in a bias sense, then other analysis approaches should give nearly equivalent results, such as a suitable post-analysis filtering of shorter-arc results. The latter approaches could prove more economical or better suited for some applications. On the other hand, achieving long-term continuity by removing offsets in overlaps between successive arcs can lead to an accumulation of systematic errors, as shown by R. Dach (workshop presentation).

It is generally thought that the precision of clock estimates within a given analysis arc could be better than indicated by the formal errors because the relative clock estimates are determined mostly by the carrier phase observations (provided that sufficiently long spans of continuously

connected and overlapping phase data are maintained for each station-satellite pair). This expectation has been supported by several experiments (Bruyninx et al., 1998; Petit et al., 1998) but only for zero- and short-baseline tests where an independent ground truth can be established. Due to differences in common-mode error cancellation, these results cannot be safely extrapolated to longer baselines, which generally show stabilities roughly consistent with the formal errors of the clock estimates ($\sim 2 \times 10^{-15}$ averaged over 1 day); e.g., Larson et al. (2000) and Dach et al. (1999). The RMS agreement among IGS Analysis Centers (ACs) for satellite clocks and receiver clocks from the global network is also at the formal error level, around 100 to 200 ps. This seems to indicate that the different analysis methods are reasonably consistent with each other and that similar procedures are being used to handle observation biases.

It is recommended that a group report be prepared and published to document the current state of understanding of the accuracy of geodetic clock estimates, their precision, and the dominant error sources. Analysis methods to minimize the effects of uncontrollable errors should be identified.

New IGS clock combination products

Since 26 December 1999 a new clock combination program is being tested in the IGS Final combinations; since 19 March 2000 the program is also being tested in the IGS Rapids. The main new element of this procedure is that it uses the clock solutions from the individual IGS

ACs as given in the clock RINEX format, rather than the orbit files (sp3 format) of the past. This format allows the inclusion of both satellite and station clocks and is flexible with respect to the sampling rate of the clock estimates. The methods used in the new combination are described in the accompanying report by Kouba and Springer (2000). Until now, the experimental products of the new Final and Rapid clock combinations have been made available on the ftp site at the University of Berne (<ftp://ftp.unibe.ch/aiub/springer/clock>). These products consist of one summary file and one clock RINEX file per day. The sampling of the clock RINEX products is 5 minutes; some ACs provide higher sampling rates.

It was agreed that the new combination scheme will become official, replacing the old combination scheme on 5 November 2000. The summary information of the clock combination will be incorporated into the normal IGS combination summary files. However, the current detailed clock summary files will be made available separately for use by the IGS/BIPM Pilot Project.

IGS clock alignment strategies

The underlying time scale for the IGS clock products is based on a linear alignment to broadcast GPS time for each individual day separately. As a result, the day-to-day stability of the IGS clocks is limited by the stability of GPS time itself, which is much poorer than that of many of the receiver clocks in the IGS network. The ending of Selective Availability on 2 May 2000 has not improved the performance of GPS time over time scales longer than a day. One goal of the

Pilot Project, to provide a linkage of the IGS clock products to UTC (CCTF, 1999), would address the time scale stability problem but requires instrumental calibrations and data sets which are not yet available. In the meantime the IGS plans to implement before 2001 an algorithm to synthesize an internal IGS time scale by relying on the large number of stable frequency standards available in the global receiver network. This internal time scale, formed from one-day batches of new data, will need to be steered to remain reasonably close to predicted UTC and will be used as the reference for distributed IGS clock products. If practical, it could be designated UTC(IGS), for example, and IGS clock products could be considered for submission to the BIPM. As calibrated geodetic receivers become available in the future, the steering of the internal time scale could be modified. If the BIPM begins to produce a predicted UTC realization (see below), then this would be preferred for long-term alignment of the IGS time scale.

Handling of observation biases

It is very clear that biases between observable types exist which depend on the individual satellite as well as on receiver type. In particular, codeless receivers operate with different distinct pseudorange tracking technologies, some relying on the narrowband C1 (or C/A) modulation while others use the wideband P1 code. Satellite-dependent biases are observed between C1 and P1 of up to ± 2 ns. This is of no significance for data analysts who process only carrier phase observables. For analysts who use the pseudorange observations, their estimates for satellite clocks can be affected. For external timing comparisons, these and other

biases must be measured and accounted for as part of the instrumental calibration. For comparisons and combinations of analysis results, consistent sets of biases and procedures must be applied. For the P1-C1 biases, the IGS has adopted a correction procedure and a recommended set of bias values (Ray, 2000). The JPL AC (Jefferson et al., 2000) has agreed to maintain the bias table by providing updates as the satellite constellation evolves. There is good evidence that different receiver models of similar types respond to the satellite-dependent P1-C1 biases in slightly different ways. Further research is needed to clarify these receiver-dependent effects and to devise methods to minimize their effects on geodetic clock estimates.

Prediction of satellite clocks

With the ending of Selective Availability, which previously limited civilian access to GPS time to about 80 ns (RMS) for real-time users, new opportunities may now exist for using broadcast time. In particular, prediction of GPS satellite clocks might be sufficiently accurate for many real-time users. Zumberge and Gendt (2000) used clock extrapolation models to estimate the average clock prediction error after 12 hours should be about 142 cm (4.7 ns). Kouba (2000) made similar projections based on the statistical behavior of different clock types. USNO began contributing clock predictions for the IGS Ultrarapid combinations in July 2000 based on extrapolations of the estimated satellite clock values from the observational data preceding the prediction period. The actual performance of these clock predictions has been about 10 ns RMS over 24 hours. Given two Ultrarapid updates each day, the expected real-time

performance should be roughly 5 ns RMS. The impact on an estimate of a user's receiver clock would be reduced by the square-root of the number of satellites tracked, or a factor of about 3. Thus, real-time user clock errors of a few ns appear entirely feasible. At this level, the instability of GPS time itself will be a major error source.

The IGS ACs are encouraged to develop clock prediction strategies based on observed clock states and to include these in their submissions for the IGS Ultrarapid products. The IGS Central Bureau is asked to assess user requirements in this area and to evaluate the utility of clock predictions for various real-time user segments. The possibility of adding satellite clock accuracy codes to the sp3 format, analogous to the existing orbit accuracy codes, should be investigated.

BIPM plans for a possible real-time prediction of UTC

The BIPM is responsible for the calculation and dissemination of the two conventional time scales, TAI and UTC. At present, UTC is computed from monthly clock comparison data and available in the form of UTC-UTC(k) within 15 days after the last standard date of the month. The IGS clocks for satellites could be aligned by comparison to some predicted realization of UTC which should be as close as possible to UTC and available on a near-real time basis. Similar scales are available presently through the individual laboratory values UTC(k), but it would be more desirable if a real-time prediction of UTC could be made on the basis of several individual values of UTC(k) provided by a set of participating labs. This will be possible if time

laboratories equipped with the best clocks in TAI become engaged to provide their clock data and links in real-time on a regular basis. The BIPM is in the process of automating the calculation of TAI, thus shortening the time delay in the calculation of TAI and UTC. The calculation procedure for a real-time prediction of UTC should follow the same principles as those of UTC. Analysis performed at the BIPM suggests that it is possible to do so and maintain agreement with UTC within a few nanoseconds.

The BIPM is encouraged to pursue these investigations, and the time labs participating in TAI and equipped with good clocks are asked to cooperate in this effort. A short-term pilot experiment is envisioned once the algorithm and process of calculation have been fixed and tested using archived data.

INSTRUMENTAL CALIBRATION

The traditional definition of calibration ("set of operations that establish ... the relationship between values indicated by a measuring system ... and the corresponding values realized by standards") would apply but there is no standard in the area of GPS receivers. So we consider an hypothetical ideal GPS system and we try to evaluate how, and by how much, measurements obtained from geodetic receivers would differ from ideal measurements and, when applied to time and frequency comparisons, how and by how much the results would differ from ideal ones.

Somewhat arbitrarily, the subject is divided in three areas: 1) the receiver system itself, 2) the link between the receiver and the clock to which it is referenced, 3) the link to the satellite clock. Items 1 and 2 must be considered for all clock comparisons while item 3 might be, in first approximation, thought to vanish when comparing the reference clocks of two receivers. However the situation is more complex partly because biases in item 3 may be receiver-dependent and partly because of the correlations between the clock results in a global solution. Only the first two items will be treated here because the item 3 biases have already been discussed above (see also Jefferson et al., 2000).

Geodetic receiver systems

Two approaches can be considered for calibration of hardware biases:

Absolute determination — An end-to-end calibration can be made by using a signal simulator which is itself assumed to be calibrated (i.e., it is in fact the assumed standard). Uncertainty on the order of 1 ns seems feasible.

Relative determination — Differential calibration can be made by comparison of measurements with those of another "reference" system (i.e., the other system is the assumed standard). Relative uncertainty on the order of 1 ns seems feasible, however uncertainty in the calibration of the reference system is presently higher.

Both methods have recently been applied to an Ashtech Z12-T. An end-to-end absolute

calibration has been carried out at the Naval Research Lab and a differential calibration has been performed at the BIPM. The results agree within the stated uncertainties (Petit et al., 2000).

Groups are strongly encouraged to exploit practical absolute and differential hardware calibration methods suitable for geodetic GPS receiver systems. These are needed most urgently for deployments at timing laboratories and other facilities equipped with stable frequency standards. The methods used for the calibration should be well documented. Specifically, a special session will be convened at the 15th European Frequency and Time Forum, in March 2001, to present progress reports in the calibration (absolute and differential) for all available Ashtech Z12-T (at least) receivers suitable for time transfer.

Link to station clock

Two approaches can be considered for the difference between the internal clock of the geodetic receiver system and the external station clock. In the external lock method, the receiver locks its internal reference to the external reference so that there is, in principle, a constant offset between both. In the internal realization method, the receiver provides an output realization of its internal reference which is measured with respect to the external reference. This method requires additional measurements (and possibly processing) to determine the link to the station clock. In both cases, the calibration of this link must be made in the same process as the calibration of the receiver system. Work is underway to determine the stability of this link and its repeatability under external events, such as power cycles.

INTER-TECHNIQUE COMPARISONS

Each new time transfer technique must be compared and validated against the standard technique(s). Doing so requires firstly a thorough understanding of the results of each technique and secondly that the entire information necessary to perform the comparison is available. Both requirements are non-trivial, particularly with techniques developed in separate scientific communities. The exchange of appropriate information is a key issue in this context.

Exchange of information

Promoting the exchange of information, knowledge, and expertise within the timing and the GPS communities is a primary goal of the IGS/BIPM Pilot Project. The establishment of the IGS/BIPM web site has been an important step in that direction. It is currently the most comprehensive source of information in the field. Moreover there is a need for a rapid information exchange medium as well as for a discussion forum. This is classically accomplished by an e-mail service, an example being the IGS MAIL service. The current informal mail exploder 'GPST' should be re-established as an automated mail server at the IGS Central Bureau, with a mirror at BIPM.

Station Descriptions and Logs

In order to analyze the data certain information about the station configuration is needed. The required information may vary depending on the type of analysis (processing of raw GPS data, processing of raw TWSTFT data, comparison of GPS and TWSTFT, etc.). In the IGS community this kind of information (including the change thereof) is maintained by the IGS Central Bureau in so-called station log files. However, the latter do not yet contain all the information required for time and frequency transfer applications. Station information relevant for time and frequency transfer should be identified and added to the station logs. The IGS logs for timing labs should in particular include information about the ties to the local UTC of the laboratory. The other time transfer techniques — TWSTFT and GPS common view (CV) — should also establish a standard, machine readable format for similar station information. These station log files should be openly accessible to all analysts.

Other types of timing information should also be collected by all techniques, such as logging of receiver clock discontinuities, calibration values, hardware configurations, and related quantities.

An ad hoc working group should identify the most appropriate formats and routes for exchanging the information needed, with representatives from the BIPM and the various techniques. Likewise, in order to compare station clock estimates from different techniques the technique-specific results must, first of all, be made available by the analysis centers in a standard format. It is suggested that the existing clock RINEX format could be extended to accommodate clock results from TWSTFT and CV. For timing labs, the results should be referred to the local UTC realization and the timing ties to the clocks of the geodetic GPS receivers should be documented. These ties must include calibration terms for the GPS

equipment.

Future combination of results

Although a discussion of a future combination of clock estimates from different techniques may be premature, the communities should devise the presentation of their results with this perspective in mind. Ideally, a common format, independent of the measuring technique, should be envisaged. The final combination should take advantage of each technique's strengths and introduce the individual results in a correct way into the adjustment process. This, however, requires adequate information from each technique and each analysis.

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