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New Timing Products from the IGS: IGS/BIPM Time Transfer Pilot Project and UT1-like Estimates from GPS

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Abstract

The International GPS Service (IGS) and its Analysis Centers are engaged in developing new products related to timekeeping, some of which are relevant to the IVS community. Global comparisons and techniques for dissemination of atomic time are being developed in a Pilot Project with the Bureau International des Poids et Mesures (BIPM). Full project information is available at http://maia.usno.navy.mil/gpst.html. In addition, high-quality estimates of Universal Time are now being made based on the observed motions of the GPS orbit planes. While these cannot replace the need for VLBI determinations of UT1, they are nonetheless very valuable for densifying the VLBI-based time series and for providing extremely rapid turnaround results necessary for real-time applications.

1. IGS/BIPM Time Transfer Pilot Project

The "IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons using GPS Phase and Code Measurements" was authorized in December 1997 jointly by the IGS and the BIPM. A Call for Participation was issued shortly afterwards with responses received from about 35 groups. The respondents have formed a working group, which was formally initiated on 18 March 1998 and is co-chaired by F. Arias, BIPM, and J. Ray, U.S. Naval Observatory (USNO).

A number of groups have been working for several years to develop the capability of using geodetic GPS techniques for accurate time and frequency transfer. A variety of convincing demonstrations has already been performed showing the potential for determining clock differences at the level of a few hundred picoseconds or better. The current state of maturity of both the global GPS tracking network and data analysis techniques now allows practical applications to be considered. The central goal of this Pilot Project is to investigate and develop operational strategies to exploit GPS measurements for improved availability of accurate time and frequency comparisons worldwide. This will become especially significant for maintaining the international UTC time scale as a new generation of frequency standards emerges with accuracies of 10^{-15} or better.

The respective roles of the IGS and BIPM organizations are complementary and mutually beneficial. The IGS and its collaborating participants bring a global GPS tracking network, standards for continuously operating geodetic-quality, dual-frequency GPS receivers, an efficient data delivery system, and state-of-the-art data analysis groups, methods, and products. The BIPM and its timing laboratory partners contribute expertise in high-accuracy metrological standards and measurements, timing calibration methods, algorithms for maintaining stable time scales, and formation and dissemination of UTC. The progress of the Project and other related information is maintained at the Web site http://maia.usno.navy.mil/gpst.mil.

2. Project Activities – Deployment of GPS Receivers

In addition to the GPS receivers already installed as part of the IGS global tracking network, other receivers at laboratories having accurate time standards are sought. These should be high-quality geodetic receivers capable of recording and rapidly transmitting dual-frequency pseudorange and carrier phase observations. The station configuration and data distribution should conform to IGS standards and appropriate documentation must be filed with the IGS Central Bureau. A log file should be completed and sent to the IGS Central Bureau for each IGS station. For this Project, due consideration should be given to electronic stability, environmental control, and other factors which might affect the timing results. Upgrading of existing tracking stations for better timing performance is also encouraged. Deployment of dual-frequency GLONASS receivers, especially collocated at IGS sites, would provide an additional data source of interest.

The IGS network currently consists of about 200 permanent, continuously operating geodetic stations globally distributed. Of these, external frequency standards are used at about 30 with H-masers, 20 with cesium clocks, and 20 with rubidium clocks. Most of the remaining sites rely on internal crystal oscillators. Currently 13 IGS stations are located at timing laboratories; additional installations are under development.

3. Project Activities – GPS Data Analysis

Strategies for analyzing GPS phase and pseudorange observations are required, consistent with other IGS products, to allow the routine, accurate characterization of time standards at a large number of independent GPS receiver sites and onboard the GPS satellites. This work is being done in close cooperation with the IGS Analysis Center Coordinator.

Of the IGS Analysis Centers, all but two already provide satellite clock estimates, which are combined and distributed with the IGS orbit products. The IGS is in the process of expanding its operational products to include combined clocks for the tracking receivers as well. A detailed plan for doing this was developed and considerable progress has been achieved.

4. Project Activities – Analysis of Instrumental Delays

In order to relate receiver clock estimates derived from GPS data analysis to external timing standards it is necessary to understand the instrumental electronic delays introduced by the associated hardware. There are, as yet, no geodetic receiver systems for which the timing calibration bias is known. This situation is a fundamental challenge to exploiting GPS geodetic techniques for time transfer. Two types of instrumental calibration approaches are being pursued by various groups. One method characterizes the delay through individual components of the receiver system. A second method attempts the end-to-end calibration of a complete (or near-complete) system by injecting simulated GPS signals. Both methods involve significant technological feats. Generally, the first method is more accessible, at least for certain components, and has the advantage of permitting the most sensitive system elements to be identified. An overall accurate system calibration determination, which is ultimately required for time transfer applications, can be difficult to obtain, however. The end-to-end methods are clearly desirable for practical uses but they require unique, expensive test equipment and may not be suitable for routine operational settings.

The level of understanding and control of environmental factors that affect frequency compar-

isons is much more advanced than time calibration. Standards of metrological control are well known in the timing community and have been implemented to varying extent at several IGS stations. Frequency comparisons at the level of 10^{-15} over one day, or better, appear entirely feasible already provided that care is taken to minimize environmentally induced variations (e.g., Bruyninx et al., 1999; Petit et al., 1999).

5. Project Activities – Time Transfer Comparisons

Simultaneous, independent time and frequency comparison data are needed to compare with the GPS-derived estimates. Collaborations are sought with groups performing time transfer experiments using a variety of techniques, particularly two-way satellite time transfer. Close cooperation is maintained with the Consultative Committee for Time and Frequency (CCTF) of the Comite International des Poids et Mesures (CIPM).

6. Project Objectives – Accurate and Consistent Satellite Clocks

Satellite clock estimates are among the core products of the IGS (Kouba et al., 1998). The IGS combined solutions for satellite clocks are distributed together with the IGS combined orbits in the sp3 product files. It is essential that the clock information be as accurate as possible and also that it be fully consistent with the other IGS products. Kouba et al. (1998) describe the importance of global consistency to ensure that the point positioning technique (Zumberge et al.,1997) can be applied without degradation.

A type of point positioning likely to become increasingly important is for tracking low Earth-orbiting satellites equipped with onboard GPS receivers. For this application the 15-minute tabulation interval of the sp3 orbit files is not adequate because the SA corruption of the broadcast clocks does not allow accurate interpolation over intervals longer than about 30 s (Zumberge et al., 1998a). For this and other applications, the IGS has been asked to consider providing satellite clock products with 30-s sampling rates. Methods for efficiently computing high-rate satellite clocks have been presented by Zumberge et al. (1998b) and Soehne (1998). A new exchange format has been developed that can permit easy distribution of the new high-rate clock results.

7. Project Objectives – Accurate and Consistent Station Clocks

Presently, the IGS does not produce clock information for the GPS ground stations although doing so is mentioned in the IGS Terms of Reference. There is a clear interest in the user community for this information. Apart from time transfer uses, it could be used to characterize and monitor the performance of station frequency standards. Clock solutions from stations equipped with very stable frequency standards (especially H-masers) are needed to apply the method of Zumberge et al. (1998a) to estimate high-rate satellite clocks. For this purpose, station clock determinations at intervals of about 5 minutes can be accurately interpolated to the 30-s intervals needed to solve for the satellite clocks provided that the ground stations are referenced to stable clocks.

For time transfer applications, such as envisioned for this Pilot Project, accurate analysis results for the station clocks are mandatory. As with high-rate satellite clocks, a suitable exchange format is required and has been developed. Preliminary summary reports to describe the analysis results characterizing satellite and station clocks are available, which will soon become an official IGS

product.

From geodetic analyses of the GPS data, the effective clock of each station is determined for the ionosphere-corrected L3 phase center of the antenna displaced by the electronic delay to the point in the receiver where the time tags are assigned to the pseudorange measurements. These clock determinations are relative measurements in the sense that usually a single station is chosen as a time reference and not adjusted. From the viewpoint of geodetic applications, the precise reference point of the analysis clocks is irrelevant. As a result, manufacturers of geodetic receivers have generally not taken care to provide easy or accurate access to the time reference points. However, for timing applications, such as time transfer comparisons with other techniques, the precise location of the clock reference and accurate access to it are essential. Consequently, the investigation of instrumental path delays and access points is critical to the success of the Pilot Project. The effects of environmental influences are generally important and must be minimized. Doing so will require new approaches for isolating GPS receiver equipment, such as efforts by Overney et al. (1997).

8. Project Objectives – Accurate and Stable Reference Time Scale

Ultimately, it is necessary that all clock information, for satellites and stations, be referenced to a common, consistent time scale. Individual sets of results from different Analysis Centers generally refer to different reference clocks. Thus, in the IGS combination process, the individual submissions must be realigned. This is currently done by choosing one submission as a reference solution, realigning its satellite clock estimates to GPS time based on the broadcast clocks for all the satellites (using only daily offset and rate terms), and then realigning all the other submissions to the reference solution (Springer et al., 1998). Corrections are applied to each solution set to account for radial orbit differences compared to the IGS combined orbits. The IGS combined satellite clock estimates are then formed from the weighted average of the realigned, corrected submissions.

It has been suggested that the clock realignment and combination process would be improved if a common set of fiducial station clocks were used in all analyses and included in the IGS submissions (Springer et al., 1998). Naturally, only stations equipped with very stable frequency standards (preferably geometrically well distributed) should be considered as candidate fiducials. Recommendations for this station set have been adopted.

Likewise, it is questionable whether GPS time is an appropriate choice for the underlying IGS time scale. The ideal choice should be accurate, accessible, and stable over all relevant time intervals (namely, 30 s and longer). GPS time is readily accessible but not with an accuracy comparable to other IGS products due to SA effects. Nor is GPS time particularly stable. The clocks of the GPS constellation are monitored from USNO and this information is provided to GPS operations with the goal of maintaining GPS time within 28 ns (RMS) of UTC(USNO), allowing for accumulated leap second differences. In practice, the two time scales have been kept within about 6.5 ns (modulo 1 s) over the last two years (for 24-hour averages). However, the GPS time steering algorithm has a bang-bang character resulting in a saw-tooth variation with a typical cycle of about 25 days. This is equivalent to a frequency error greater than 10^{-14} over days to weeks, which changes periodically in an abrupt, nearly step-like fashion.

Almost certainly, an internal ensemble of the frequency standards used in the IGS network can be formed which would possess better stability than GPS time (Young et al., 1996). There are

currently about 30 IGS stations using H-masers, and about 40 with cesium or rubidium standards. Addition of new IGS sites located at primary timing laboratories would only improve this situation. A purely internal IGS time scale would not be stable against long-term drifts so some linkage to external laboratory time scales is required. Indeed, traceability to UTC is most desirable. In principle, this could be accomplished using the instrumental calibration data mentioned above, especially for the fiducial clock sites. It will be technically difficult, however, to achieve comparable accuracies for the calibration measurements to the few hundred picosecond level possible for the data analysis clocks. This will be one of the greatest challenges for this Pilot Project.

An alternative approach to provide external linkage that can be readily implemented uses monitor data for the GPS constellation that are collected and compared at the timing labs. USNO collects such data using pseudorange timing observations and makes the results publicly available. Using the observed offsets of GPS time relative to UTC(USNO), the corresponding IGS clock estimates can be related to UTC(USNO). Because of the effects of SA such comparisons would only be useful to remove long-term differences. This is probably sufficient, at least for an initial realization. Other timing laboratories would be encouraged to provide similar monitor data for a more robust tie to UTC. A potential problem with this approach is possible biases between the effective clocks transmitted by the satellites as measured from the pseudorange and carrier phase observables.

Apart from the issues discussed above concerning calibration and external referencing for an IGS time scale, there are other practical questions that must be resolved. In particular, it may be difficult to form and maintain a time scale within the IGS product delivery schedule. This is likely to be especially true for the Rapid products even though that is probably also where the greatest user interest lies. Fundamentally, this does not seem overwhelming although it will require entirely new and highly automated IGS processes. Other practical concerns are minimizing discontinuities at day boundaries, dealing with clock discontinuities and drop-outs in the ensembling process, and finding an appropriate robust ensembling algorithm. These subjects, together with those mentioned above, should be studied during this Pilot Project.

9. UT1-like Estimates from GPS

UT1 cannot normally be estimated in the analysis of satellite tracking data used also to determine the satellite orbit. The UT1 rotation angle is perfectly correlated with the ascending node of the orbit. However, if a priori constraints are applied to the node parameter, such as by imposing continuity with the preceding data arc, then UT1-like variations can be estimated. Such constraints can risk degrading the orbit determination so they are not commonly used. The EMR Analysis Center (at Natural Resources Canada, Ottawa) is the only IGS group which uses this method.

Length of day (LOD) can normally be estimated and this is routinely done in high-accuracy GPS analyses. There is a perfect correlation between LOD and the rate of change of the ascending orbit node, but the latter is not ordinarily an adjusted parameter. On the other hand, any error in the modeling of the node rate will cause an error in the LOD estimates. In particular, GPS-based LOD estimates tend to be sensitive to biases, which is equivalent to a net nodal drift of the constellation.

All IGS Analysis Centers provide LOD estimates, which are combined after bias-correction and weighting based on comparison to the IERS Bulletin A series for a recent 21-day sliding period

(Mireault et al., 1999). The combination and the best individual submissions have random short-term errors (after bias correction) of roughly 20 μs and larger. The GPS-based LOD time series can be integrated to form a UT1-like series, where the errors will behave as a random walk (Ray, 1996).

In the IERS Bulletin A combination (for rapid service and prediction applications), the most recent IGS combined LOD values are integrated and included for epochs after the latest VLBI data. The 21 most recent days of directly estimated UT1-like values from EMR are also included, after calibration in offset and rate by comparison with overlapping VLBI results.

10. New UT1-like Series from USNO

Kammeyer (2000) has developed an alternative technique for extracting UT1-like variations by comparing observed, Earth-fixed GPS satellite ephemerides to numerically propagated models of their orbital planes. The modeled orbit planes are propagated using empirical models for the orbit-normal component of the radiation pressure acceleration. These models are expressed in terms of the angle from the orbital angular momentum to the Sun direction and the angle from the projection of the Sun direction onto the orbit plane to the position vector of the satellite. For each satellite and each time, there is a unique axial rotation angle which brings the observed Earth-fixed positions into alignment with the propagated orbit plane. The difference between the ascending node of the modeled orbit plane and that of the actual orbit plane for each satellite causes this rotation angle to differ by an offset from Greenwich apparent sidereal time. Adding to the rotation angle an estimate of this offset gives a single-satellite estimate of sidereal time and equivalently of UT. Taking the median of these estimates for the 12 satellites modeled (soon to increase to 16) gives the UT estimate reported to IERS Bulletin A.

By comparison with VLBI results, we have established that Kammeyer's GPS-based series has errors which can be characterized by two components which should be added in quadrature. The short-term noise floor is approximately white and has a variance of about $(25\ \mu\text{s})^2$. As with any satellite-based determination, there is also a random walk component, the variance of which is about $40\ \mu\text{s}^2 \times \text{t}$ where t is the duration in days since calibration with VLBI. This performance is much better than for any other satellite-based estimates, particularly for the long-term behavior.

IERS Bulletin A has grown increasingly reliant on the IGS estimates of LOD and UT1-like variations, especially since the development of Kammeyer's series. In June 1999, the method used to assimilate the latter series was changed to incorporate it entirely beginning 8 July 1998, rather than only for the most recent period. A calibration trend is computed and applied based on a smoothing of low-frequency differences compared with VLBI. Calibration of the most recent GPS results, after the end of the latest VLBI data, is based on an ARIMA model extrapolation of the earlier low-frequency trend. This new assimilation method provides better UT1 values in the historic Bulletin A series by improving the "interpolation" where gaps in VLBI data occur. It also provides better rapid service performance by enhancing the stability of "extrapolation" after the latest VLBI data. Note that the GPS results from the IGS Rapid product delivery are available daily at 17:00 UTC for the previous day. This very rapid turnaround relieves the pressure for fast turnaround of VLBI Intensive data. However, it does not remove the critical need for frequent VLBI observations which remain necessary for calibration of the GPS-based results and for the development of the underlying empirical orbit models.

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