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IGS/BIPM PILOT PROJECT TO STUDY TIME AND FREQUENCY COMPARISONS USING GPS PHASE AND CODE MEASUREMENTS

Interim Report

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INTRODUCTION

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 International GPS Service (IGS) and the Bureau International des Poids et Mesures (BIPM). Following a Call for Participation, a working group was formed in March 1998 by the >35 groups that responded. Co-chairing the Project on behalf of the IGS is Jim Ray (U.S. Naval Observatory, USNO) and for BIPM is Elisa Felicitas Arias (BIPM).

The central goal of the Pilot Project is to investigate and develop operational strategies to exploit GPS measurements and geodetic techniques for improved availability of accurate time and frequency comparisons worldwide. This is becoming more significant for maintaining the international UTC timescale as a new generation of frequency standards emerges with stabilities 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 timescales, 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.html`. Please refer to the status report delivered for the 14th Meeting of the CCTF for a detailed description of the organization of the Project and its objectives (Ray and Petit, 1999).

STATUS OF RECENT ACTIVITIES

Workshop — September 2000

The IGS held its 2000 Analysis Center Workshop at USNO during 25-29 September 2000. Three broad themes dominated the overall workshop, including two days devoted entirely to the Pilot Project. The discussions at the workshop, including specific recommendations in the four main areas of activity, are summarized in the paper by Ray, Arias, Petit, Springer, Schildknecht,

Clarke, and Johansson (2001).
A copy of the workshop summary paper is attached to this report. A brief summary and the specific recommendations from the workshop are given in the sections below. In addition to these detailed recommendations, two notable milestones were set during the workshop: 1) The IGS will implement as soon as possible, at least in a test mode, the new internal time/frequency scale under development at USNO. 2) A special session on calibration issues was to be held during the 15th European Frequency and Time Forum (EFTF) in Neuchâtel, Switzerland during 6-8 March 2001. In conjunction with this session, the timing laboratories will be invited to undertake calibration trials (absolute or differential) for all available Ashtech Z-12T receivers, coordinated by the BIPM.

Status of GPS installations at timing labs

The IGS tracking network currently consists of ~250 permanent, continuously operating, geodetic stations globally distributed. Of these, almost 80 are equipped with external frequency standards, the remainder using internal crystal oscillators. The external standards in use are: ~38 with H-masers, ~23 with cesiums, and ~17 with rubidiums. The IGS stations listed in Table 1 are located at timing laboratories (as of June 2001).

Table 1. IGS stations located at BIPM timing laboratories (as of May 2001)

IGS Site	Time Lab	GPS Receiver	Freq. Std.	City
AMC2	AMC *	AOA SNR-12 ACT	H-maser	Colorado Springs, CO, USA
BOR1	AOS	AOA TurboRogue	cesium	Borowiec, Poland
BRUS	ORB	Ashtech Z-XII3T	H-maser	Brussels, Belgium
MDVO	IMVP	Trimble 4000SSE	H-maser	Mendeleevo, Russia
NPLD	NPL *	Ashtech Z-XII3T	H-maser	Teddington, UK
NRC1	NRC *	AOA SNR-12 ACT	H-maser	Ottawa, Canada
NRC2	NRC *	AOA SNR-8100 ACT	H-maser	Ottawa, Canada
OBER	DLR	AOA SNR-8000 ACT	rubidium	Oberpfaffenhofen, Germany
PENC	SGO	Trimble 4000SSE	rubidium	Penc, Hungary
SFER	ROA *	Trimble 4000SSI	cesium	San Fernando, Spain
SPT0	SP	JPS Legacy	cesium	Borås, Sweden
TOUL	CNES	AOA TurboRogue	cesium	Toulouse, France
USNO	USNO*	AOA SNR-12 ACT	H-maser	Washington, DC, USA
WTZR	IFAG	AOA SNR-8000 ACT	H-maser	Wettzell, Germany

* participates in TWSTT operations

In addition to these, several time labs are equipped with geodetic receivers which are not yet incorporated into the IGS network but for which data are publicly available. Some of these are listed in Table 2.

Table 2. Additional BIPM timing labs equipped with geodetic receivers (as of May 2001)

IGS Site	Time Lab	GPS Receiver	Freq. Std.	City
LPTF	LPTF	Ashtech Z-XIIT	H-maser	Paris, France
NPLF	NPL	Javad Legacy	H-maser	Teddington, UK
ROAH	ROA	AOA TTR4-P	cesium	San Fernando, Spain

Progress with installation of IGS stations at timing laboratories has been slow. Thus far, none of those that do operate has been calibrated. Recently, however, the techniques to do so, at least for the Ashtech Z-12T model, were developed by Petit, Jiang, White, Beard, and Powers (2001) so progress in this area can be expected in the near future.

SUMMARY OF IGS WORKSHOP

Data analysis

The two-day meeting had four segments related to the Pilot Project plan. J. Ray (USNO) gave an overview of data analysis issues, presenting evidence showing an observed accuracy for GPS-based clock estimates which is larger than the formal errors ($\sim$125 ps) by roughly a factor of four. There are large variations among sites and a few are much worse, but the main error sources (including code multipath, receiver temperature variations, etc) remain to be quantified. Evidence indicates that longer analysis arcs may give improved clock accuracy due to greater code averaging. Simulations by R. Dach (AIUB) support this, but also illustrate some possible dangers of accumulated systematic errors if long-term continuity is enforced by overlaps between arcs. Not yet studied are alternative filtering approaches of short-arc data to accomplish equivalent results. The short-term precision of clock estimates is even less clear, though long baseline results generally fail to find stabilities better than about 2×10^{-15} averaged over 1 day, roughly consistent with the formal errors. Results from different analyses also agree at about this same level.

T. Springer (AIUB) described the new methods he has implemented to combine satellite and receiver clock estimates from the IGS Analysis Centers. These ran in a demonstration mode starting at the beginning of 2000, with comparison results published in the regular Final and Rapid combination reports. The new "clock RINEX" format is used for the exchange of estimates and for the distribution of results. The new clock combination adds considerable robustness and outlier detection, which requires far less manual intervention, as well as the new receiver clock products. These became official on 5 November 2000.

Unfortunately, the usefulness of the current IGS clock products is somewhat limited by the underlying time scale, which is based on a linear alignment to broadcast GPS time for each day separately. Large day-to-day discontinuities in time and frequency are seen. K. Senior (USNO) presented a Kalman filter method of generating an internal time scale from an integration of combined IGS frequency standards. He proposed to implement this approach within the IGS clock combination in the near future. The longer-term steering of such a time scale will probably be loosely aligned to GPS time, at least until calibrated links to UTC become available.

J. Zumberge (JPL) and Ray discussed the prospects for predicted satellite clocks in the post-SA era. Over 24-hour spans, the IGS already does about as well as the broadcast GPS clocks ($\sim$10 ns RMS). With more frequent updates, such as the 12-hour interval of the IGS Ultra-rapid products, the IGS performs better raising the possibility of providing global access to time at the $\sim$2 ns level. The instability of GPS time (to which IGS clock products are currently aligned) is the major error source, although the older satellite clocks also cause problems.

F. Arias (BIPM), representing G. Petit (BIPM), described the IGS products already being used to improve intercontinental time transfers for UTC/TAI. These chiefly involve ionosphere maps to correct single-frequency common-view receiver data and precise GPS orbits. She also reported work in progress at the BIPM Time Section to automate the process of computing UTC/TAI, which will facilitate moves to a possible predicted form of UTC for real-time use. Petit is already studying this subject and BIPM expects to begin a pilot experiment in the near future.

Instrumental calibration

An introduction to the important subject of instrumental calibration, prepared by Petit, was presented by P. Defraigne (Royal Observatory of Belgium), followed by a report from J. White (NRL) on their laboratory work. An end-to-end calibration has been made for an Ashtech Z12-T receiver and antenna, as well as for several components. Some issues remain to be resolved, but prospects seem promising for an absolute calibration at the ns level, at least as good as for current single-frequency receivers. Z. Jiang (BIPM) described the corresponding differential calibration approach comparing the Z12-T to a calibrated NBS timing receiver. The consistency of these two independent methods was later established to be in agreement within the expected errors. E. Powers (USNO) reported work underway to modify AOA receivers to accept external 1 pps synchronization, similar to the Z12-T.

The effects of inter-code satellite biases were well covered by Y. Gao (University of Calgary) and S. Schaer (AIUB). Differences between the C/A (C1) and P1 modulations are up to +/- 1.7 ns depending on the satellite. Gao showed that there also exist smaller receiver-dependent differences, the cause of which is not understood. The CODE Analysis Center estimates the P1-C1 differences daily, as well as P1-P2 biases needed to interpret ionospheric results, and posts the results publicly. Later in the week, M. Heflin (JPL) presented analyses on behalf of D. Jefferson (JPL) demonstrating the improvements obtained using the current IGS P1-C1 bias convention.

For time transfer, the relationship between an external reference and the internal receiver circuitry must be accurately known. J. Clarke (NPL) described their evaluations of the Javad Legacy receiver, finding it to be an intriguing possibility for the future but needing further study. Jiang related similar experiences with the Z12-T in Paris.

The effects of environmental changes, especially temperature, on frequency stability have been well documented by Defraigne and her colleagues in Brussels, as well as by the BIPM group. Updates of these results were presented. The most sensitive components seem to be cables (for which very stable types are available) and the receivers. For timing applications, strict control of the receiver environments is essential. The effects of other influences (e.g., magnetic fields and humidity) have not been studied.

Inter-technique comparisons

Th. Schildknecht (AIUB) offered several proposals to facilitate the exchange of clock information between groups and techniques; e.g., by standardizing the logging of station configuration data. In addition to aiding comparison studies, this should simplify and improve the computation of TAI in the future. Reviews of the ongoing comparison campaigns between common-view, two-way satellite, and geodetic time transfer methods were presented by Clarke (for his NPL colleagues) and by L. Nelson (NIST). Interpretation of the geodetic time transfer results is complicated by the inevitable changes that have occurred at the stations.

Station installations

The final timing session dealt with station installation issues. J. Johansson (Onsala Observatory) gave an overview of geodetic aspects, including monumentation, antenna mounts, and radomes; Clarke covered the hardware aspects, with an emphasis on the concerns for timing. In some ways, the two perspectives are distinct, but they can mesh harmoniously. Examples from the Brussels, USNO, and Haystack Observatory groups were offered. Defraigne has developed software to create BIPM common-view schedules from raw 1-second Ashtech Z12-T observation files, which will simplify operations at timing labs by eliminating the need for separate timing receivers. R. Hambly (CNS Systems) showed the impressive results he and T. Clark (NASA) have obtained, now that SA is turned off, using a very inexpensive single-frequency timing receiver.

SPECIFIC RECOMMENDATIONS FROM IGS WORKSHOP

Network

TN1. Integration with IGS network. All timing labs are encouraged to install suitable dual-frequency geodetic receivers and integrate these into the IGS network. The continued support of the IGS Central Bureau is urged, of offering advice, suggesting experts to contact, and displaying example sites and monument on the IGS website.

TN2. Hardware configuration recommendations. Participants are encouraged to:
- investigate the suitability of new hardware as it becomes available;
- investigate and report the performance of the Javad Legacy receivers;
- ensure that actions needed for IGS use of the TSA-100 antenna are completed;
- investigate the possibility to temperature-stabilize cables and receivers (especially);
- continue work to improve continuity for timing receivers across power cycles;
- support the development of software for IGS-compliant receivers to output the BIPM common-view format.

TN3. Geodetic control.
- Participants are encouraged to monitor the stability of the positions for new timing lab stations to ensure that these are adequate for use by the geodetic community.
- Timing labs are encouraged to establish geodetic control points in order to monitor the stability of the site and provide a reference when equipment changes occur at the site.
- The IGS Central Bureau is asked to identify experts in the problem of rooftop mounts so that their experience may be shared.

TN4. Environmental stability control. Participants are encouraged to:
- investigate optimal trade-offs to mitigate temperature effects;
- develop and investigate new solutions to mitigate temperature effects;
- investigate alternative cable types for temperature coefficients and suitability;
- log additional environmental data, such as humidity and EM-fields;
- investigate environmental effects other than temperature to ensure that their significance has not been overlooked;
- investigate further the effects of temperature on splitters.

TN5. Multipath mitigation. Timing labs are encouraged to assess the significance of the multipath effects at their stations in order to establish whether mitigation is a productive strategy. The UNAVCO toolbox "teqc" can be useful in doing so.

TN6. Operational Data Center for time labs. To ease the operational burdens on individual timing labs, one or more Operational Data Centers for the geodetic receivers at timing laboratories should be considered. Such an Operational Center could serve as a helpful interface between the IGS and the timing labs.

Analysis

TA1. Publish clock accuracy and precision report. A group report should be prepared and published (via the BIPM) 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 systematic and random errors should be identified. It is suggested that this report be prepared by C. Bruyninx, R. Dach, J. Kouba, K. Larson, G. Petit, J. Ray, Th. Schildknecht, K. Senior, T. Springer, and others.

TA2. Official adoption of new IGS clock products. The new clock combination scheme was made official, replacing the old combination scheme for the IGS Rapid and Final products, on 5 November 2000. This method should also be implemented in the IGS Ultra-rapid combination as soon as feasible.

TA3. IGS time scale. The IGS should implement an algorithm (being developed by K. Senior) to synthesize an internal time scale for its clock products to be less reliant on GPS time, which currently limits stability at intervals of about a day and longer. This should be done as soon as feasible, at least in a test mode. Ideally, the long-term steering should be to a predicted realization of UTC, when this can be achieved, which requires calibrated IGS receivers at timing laboratories.

TA4. P1/C1 biases. All data analysts who process undifferenced pseudorange data are urged to adopt the IGS bias conventions and values. These must be updated occasionally as the satellite constellation evolves. Since there is good evidence that different receiver models respond to the satellite-dependent P1-C1 biases in slightly different ways, further research is encouraged to clarify these receiver-dependent effects and to devise methods to minimize their impact on geodetic clock estimates.

TA5. Real-time use of UTC. The BIPM is encouraged to pursue investigations into the possibilities for providing a predicted form of UTC for real-time users. The time labs participating in TAI and equipped with good clocks are asked to cooperate in this effort. A short-term pilot experiment might be envisioned once the algorithm and process of calculation have been fixed and tested using old data.

Calibration

TC1. Receiver calibrations. Groups are strongly encouraged to develop 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. BIPM will coordinate activities in this area.

TC2. Receiver manufacture. Receiver manufacturers are urged to implement internal clock circuits which are not subject to discontinuities (e.g., due to power interruptions, etc), to improve temperature-dependent stability, and to enhance the general usefulness for timing applications. The IGS and BIPM will develop suitable specifications that can be used by manufacturers and others to better understand timing requirements. J. Clarke and Th. Schildknecht will lead this effort.

Intercomparisons

TI1. IGS/BIPM mailing list. The current IGS/BIPM e-mail exploder will be reestablished as an automated mail server at the IGS Central Bureau, with a mirror at BIPM.

TI2. Exchange of timing information. An ad hoc working group should identify the most appropriate format and route for exchanging the information needed for comparing the clocks at different stations, and inter-comparing different time transfer techniques. This will include: reporting offset discontinuities, calibration values, hardware configurations, ties to UTC(lab), analysis results, and related quantities. Th. Schildknecht and J. Clarke will coordinate the formation of such a working group with the BIPM and representatives of the other time transfer techniques.

PROPOSED CCTF RECOMMENDATION (update of Recommendation from 14th CCTF)

Time and frequency comparisons using GPS phase and code measurements

The CCTF,

considering

- that the IGS has established an infrastructure of global GPS observing network, data distribution system, robust analysis methodology, and high-quality products,
- that a joint IGS/BIPM Pilot Project exists to study time and frequency comparisons using GPS phase and code measurements,
- that calibration methods are being developed to fully exploit the capabilities of these techniques for time comparisons,

fully supports the joint IGS/BIPM Pilot Project,

and recommends

- that timing laboratories participate in the IGS by installing appropriate GPS receivers and following the IGS standards and procedures to the greatest extent possible,
- that appropriate methods be exploited to calibrate the instrumental delays relating the receiver internal reference to the external clock,
- that the IGS reference for clock products be aligned as much as possible to UTC,
- that the timing laboratories and the BIPM take the necessary steps to allow the IGS to realize this goal.

REFERENCES

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