GPS COMMON–VIEW TIME TRANSFER

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Abstract

The introduction of the GPS common–view method at the beginning of the 1980s led to an immediate and dramatic improvement of international time comparisons. Since then further progress brought the precision and accuracy of GPS common–view intercontinental time transfer, from tens of nanoseconds to a few nanoseconds, even with SA activated. This achievement was made possible, mainly by the use of ultra–precise ground antenna coordinates, post–processed precise ephemerides, double–frequency measurements of ionosphere, and appropriate international coordination and standardization. This paper reviews developments and applications of the GPS common–view method during the last decade and comments on possible future improvements, whose objective is to attain sub–nanosecond uncertainty.

I. INTRODUCTION

The excellence of world–wide unification of time realized by the establishment of International Atomic Time (TAI) and Coordinated Universal Time (UTC), depends on the quality of the participating atomic clocks and the means of time comparison. In the pre–GPS era (until the early 1980s) the technology of atomic clocks was always ahead of that of time transfer. The uncertainties of the long–distance time comparisons, by LORAN–C, were some hundreds of nanoseconds, and large areas of the earth were not covered. The introduction of the GPS has led to a major improvement in world- wide time metrology with respect to precision, accuracy and coverage.

The common–view method was suggested in 1980 by the NBS[1] and since 1983 has been used by an increasing number of national timing centres for accurate time comparisons of atomic clocks. At present, of 45 national time laboratories contributing to the establishment of TAI only 3 are not using GPS.

The nature of GPS orbits is such that satellites are observed every sidereal day at nearly the same location on the sky, so scheduled common views are repeated every 23 h 56 min. The common–view schedule, established by the BIPM and distributed to the national laboratories is kept without change for about 6 months, when a new schedule is issued. Two stations or more, following the schedule, receive the signals of the same satellite at the same time and communicate the data to each other through electronic mail, to compare their clocks. The main advantage of this method is that satellite clock error contributes nothing (GPS time disappears in the difference) so it is of utmost interest during implementation of Selective Availability (SA). The data are processed by the BIPM for the computation of international time links directly involved in the establishment of TAI and UTC.

With GPS, continental and intercontinental time comparisons are performed with a precision of a few nanoseconds. This makes it possible to measure, for integration times of only 1 day, the frequency differences between remote atomic clocks at the level two or three parts in 10^{14}. But this is by no means the limit of the possibilities of GPS. Geodesists, using a new generation of receivers, expect to measure pseudo-ranges with uncertainties of 10 cm or less and hence to reduce ephemeride errors also to less than 10 cm. These developments bring the hope that time comparisons may be achieved with uncertainties of 300 ps or less. Such performance is required to meet the challenge of the upcoming new generation of time and frequency technology.

A specific problem in the use of GPS for time transfer is that it is a one-way system. In addition, most laboratories use only the L1 frequency. This affects the propagation delay in many ways: this is so even if the common-view method, in some cases, diminishes ephemeride and ionospheric errors. Here we review these perturbations and outline possible solutions. The use by time laboratories of GPS time receivers of different commercial origin raised the question of the standardization of this equipment. Major recent progress in this domain is briefly described. Finally we report on possible assessments of the precision and accuracy of the GPS common-view method mainly by comparing it with other methods of accurate time transfer.

II. SOURCES OF ERRORS

II.1. GROUND ANTENNA COORDINATES

It has been found that inaccurate antenna coordinates (reaching sometimes several tens of metres) are the cause of large errors in GPS time transfer[2]. For 1 ns accuracy in time comparisons, ground-antenna coordinates should be known in a global terrestrial reference frame with an accuracy of 30 cm or better. In practice national time metrology laboratories use the ITRF reference frame which is similar to the WGS 84, used by the GPS, but is more accurate[3,4]. About 10% of the laboratories have coordinates at a level of 10 cm, 50% at a level of 50 cm. The remaining laboratories have coordinates with uncertainties ranging from 1 m to 10 m. Work continues for the improvement of these coordinates.

II.2. SATELLITE EPHEMERIDES

The uncertainty of the GPS broadcast ephemerides ranges from 5 m to 30 m without SA[5,6]. The common-view method reduces the impact of ephemeride error for short baselines. It ranges from one to several nanoseconds for a single common view. However for intercontinental distances the impact of this error can be amplified and in some cases may reach tens of nanoseconds for a single common view.

According to available information the error in broadcast ephemerides introduced by SA should be about 100 m. This would introduce an error for long distance common views exceeding 100 ns in some cases. At present SA does not contain the component of ephemeride degradation and takes form only of clock dither degradation.

To reduce ephemeride error for long–distance time links, post–processed precise ephemerides should be used[5]. At present, several institutions compute precise ephemerides and make them available to the public. The best known precise ephemerides are provided by the IGS, the NGS and the DMA with a delay ranging from some days to one month. Their precision ranges from 0.5 m to 3 m. The DMA precise ephemerides are expressed in the WGS 84 reference frame and those of the IGS and the NGS in the ITRF reference frame. In the case of SA ephemeride degradation, the use of precise ephemerides will be necessary[5]. The precise ephemerides are applied from October 1993 to the GPS intercontinental common–view links used for the computation of TAI.

II.3. IONOSPHERIC REFRACTION

The single–frequency C/A–code time receivers, largely used in time laboratories, compute ionospheric delay from broadcast parameters and a model which has an uncertainty that may be as large as 50% of the evaluated delay. This means that for low elevation observations, unavoidable for long distance links, and during the day, uncertainties of ionospheric delay range from 5 ns in periods of low solar activity to 50 ns in periods of intense solar activity. However, for links of up 1000 km the path through the ionosphere is approximately the same on the two observation sites and errors in the estimation of ionospheric delay almost disappear in the common–view approach. This is not the case for long distance links.

Fortunately the GPS uses two frequencies which allow us to measure the ionospheric delay. Dual–frequency codeless receivers provide measurements of ionospheric delay with an uncertainty of a few nanoseconds[7,8] and dual–frequency P–code receivers provide these measurements with an uncertainty of about 1 ns. During implementation of AS, when P–code is replaced by a Y–code which is inaccessible for non–authorized users, the P–code receivers switch automatically to codeless mode. The use of codeless and P–code receivers to measure ionosphere is still limited in time laboratories. The long distance links between Europe, East Asia and North America, used for TAI computation, are already corrected by ionospheric measurements using codeless receivers.

II.4. TROPOSPHERIC REFRACTION

At radio frequencies the troposphere is a non–dispersive medium, and its effect on pseudo–ranges and time comparisons cannot be estimated from dual frequency measurements as is done for the ionosphere[9]. Instead, models are used for the estimation of the tropospheric delay. It has been assumed that for the needs of GPS time transfer at the level of 1 ns to 2 ns, and for observations performed at elevation angles above 30°, a simple global model is sufficient. However, in the practice of common–view time transfer over long distances (9000 km), elevations of 20° are sometimes unavoidable. We have also observed that different types of receivers use different tropospheric models[10]. For example, a comparison of two receivers has shown differences of 1.0 ns at 60° elevation, 1.8 ns at 30° and 3.2 ns at 20°. To obtain an accuracy of a few hundreds of picoseconds in GPS time transfer, more sophisticated models of the troposphere with the inclusion of local meteorological measurements, will be necessary[10,11].

II.5. INSTRUMENTAL DELAYS

Several experiments on the relative calibration of receiver delays have been performed by moving a GPS receiver, used as transfer standard[12,13,14,15], between sites. The resolution is of the order of 1 ns for 1 – 2 days of simultaneous tracking. However, only few of these receivers have been checked. Some received a single visit and very few received two or more visits. Our experience concerning the long–term stability of receiver delays is limited and drifts or steps of several tens of nanoseconds could occur without being noticed. Furthermore, a sensitivity to the external temperature of some types of GPS time receivers has been reported in last few years[16].

II.6. MULTIPATH PROPAGATION

Multipath propagation arises from reflections at objects located around and under a GPS antenna. Resulting instantaneous errors can be as large as several tens of nanoseconds[17,18]. Fortunately, these errors are partially averaged over 13–minute tracks. Still, special care should be taken in the installation of a GPS antenna. An ideal installation would provide total isolation of the antenna from its environment. One approach to this ideal situation would be to install the antenna on the top of a high tower[19]. Another option is to locate the antenna directly on the ground in an open flat field with no obstacle within a radius of several tens of meters. In practice, good locations are difficult to find. In any event GPS antennas should be located in open areas and equipped with protection planes to eliminate reflection from below.

II.7. LACK OF STANDARDIZATION

For the GPS time comparisons, the receiver software, the adopted reference frames and the constants should be identical. Unfortunately, differences have been found between the receivers of different origin[10,20]. An important advance has recently been made by the Group on GPS Time Transfer Standards: a set of standards for track monitoring and data processing has been issued in the document Technical Directives for Standardization of GPS Time Receiver Software[21]. These standards should be soon adopted by receiver designers and users. The use of standardized procedures is particularly critical during implementation of SA (see paragraph on SA below).

III. GPS COMMON–VIEW TIME TRANSFER DURING SA AND AS

Selective Availability (SA) and Anti–Spoofing (AS) are intentional degradations of GPS signals and navigation messages designed to deny the full accuracy of the system to unauthorized users such as the international community of time metrology (Most authorized users of GPS belong or are affiliated to the US Department of Defense). The issue of SA and AS is closely linked to the history of the GPS. It was developed in the 1970s and may be subject to change in the rapidly evolving international environment of the 1990s.

According to information currently available, SA should consist of:

- a satellite clock dither, the effect of which is removed by a strict common view, and
- a bias in the ephemerides of about 100 meters, which changes frequently, and has an effect in common view, which is roughly proportional to the distance[22].

Up to now, SA consisted only of clock dither, except for a few short periods during which the ephemerides were also degraded. This means that the effect of SA can be entirely removed by a strict common view. At present, time receivers use different time scales (UTC or GPS time) to monitor tracks and synchronization of common views is limited to several seconds. After implementation of the standards noted above, all receivers will use a unique time scale, UTC, and synchronization of observations from remote sites will easily be completed within 1 second. To cancel all the effects of SA the receivers should also process the short period data according to a common scheme. The implementation of standards will also resolve this question.

Although present implementation of SA does not include ephemerides degradation, this does not mean that such a degradation will not occur in the future. To overcome the problem of the possible degradation of ephemerides, various approaches are being studied[6]. One of these is to derive corrections to broadcast ephemerides affected by SA from post-processed precise ephemerides.

The AS is implemented by jamming the P-code and replacing it with a Y-code accessible only to authorized users. AS affects neither single-frequency C/A-code time receivers nor double-frequency codeless ionospheric measurements systems. Of course AS does affect double frequency P-code receivers. In the case of AS these devices switch from the P-code mode of measurement of the ionosphere to the codeless mode.

IV. DATA PROCESSING

At present all GPS common-view time links used for the computation of TAI are processed at the BIPM according to a common scheme. First it is ensured that the tracking intervals at the two laboratories have strictly the same start time and length (usually 13 min) to overcome the effects of the clock dither brought about by SA. The value of the time link is then computed at the midpoint of the tracking interval. For the links between Europe and East Asia, and Europe and North America, ionospheric measurements and precise ephemerides are applied according to the method described in[6,23].

Following this a Vondrak smoothing[24] is performed on the values UTC(i)−UTC(j). This acts as a low-pass filter with a cut-off period which ranges from about 1 day for short distance links (up to 1000 km) to about 8 days for long distance links (9000 km). These periods were chosen as being approximately the limit between the time intervals in which measurement noise is dominant, and the longer intervals in which clock noise prevails. Finally, smoothed values are interpolated for 0 h UTC of standard dates (MJD ending by 9).

V. ERROR BUDGET

The typical error budget of Table I is given for distances of 1000 km and 5000 km, and for the usual tracking durations of 13 minutes, when applying the common view mode[25]. Two cases are considered: a single common view and a daily average of 10 common views. This budget is established for normal operating conditions. Much larger errors may occur in the case of a defective receiver, lack of delay calibration, poor environment of the antenna, adoption of wrong antenna coordinates, etc...

Table I. Typical error budget of GPS time comparisons in common view (CV), at distance d, C/A-code. (Unit: 1 ns)

	For a single CV		For 10 CV, average over 1 day (1)	
d=	1000 km	5000 km	1000 km	5000 km
Satellite clock error (cancels in CV mode)	0	0	0	0
Antenna coordinates (2)	20	20	7	7
Satellite ephemerides	2	8	1	3
Ionosphere (day time, normal solar activity, elevation > 30°)	6	15	1	3
Troposphere (elevation > 30°)	2	2	0.7	0.7
Instrumental delay (relative)	2	2	2	2
Receiver software	2	2	2	2
Multipath propagation	5	5	2	2
Receiver noise (13-min average)	3	3	1	1
Total	22	27	8	10

(1) The noise of the laboratory clocks and the rise time of reference pulses bring non-negligible contributions, which are not considered here.
(2) Assuming uncertainties of the order of 3 m. In practice, errors of coordinates can sometimes reach 30 m to 40 m.

Table II gives a revised error budget for GPS time links, using receivers which are presently in operation, based on the following suppositions:

Table II. Possible error budget, with optimum operation, in common view (CV), at distance d, C/A–code. (Unit: 1ns)

	For a single CV		For 10 CV, average over 1 day	
d=	1000 km	5000 km	1000 km	5000 km
Satellite clock error (cancels in CV mode)	0.0	0.0	0.0	0.0
Antenna coordinates	0.6	0.6	0.2	0.2
Satellite ephemerides	0.3	1.0	0.1	0.3
Ionosphere (measures)	1.0	1.0	0.3	0.3
Troposphere (elevation > 30°)	2.0	2.0	0.7	0.7
Instrumental delay (relative)	1.0	1.0	1.0	1.0
Receiver software	0.0	0.0	0.0	0.0
Multipath propagation	1.0	1.0	0.3	0.3
Receiver noise (13 min average)	3.0	3.0	1.0	1.0
Total	4.0	4.2	1.6	1.7

- error of antenna coordinates of 10 cm (the figures for a single CV correspond to the worst direction at both sites),
- error of satellite precise ephemerides of 1 m (in the worst direction for a single CV),
- measured ionospheric delay with existing ionospheric measurement systems,
- modelled tropospheric delay (as in Table I),
- measured relative instrumental delays by receiver transportation,
- identical and correct receiver software,
- good shielding of the antennas against multipath propagation,
- receiver noise as in Table I.

Among these suppositions, the compatibility of receiver software is not yet realized. However, the largest improvements arise from the adoption of accurate coordinates for the antennas, precise satellite ephemerides and measurement of ionospheric delay. The estimates of errors in Table II are conservative, nevertheless we observe that the contribution of GPS to the uncertainties of time comparisons at 5000 km distance, on daily averages of 10 common views, can be of the order of 2 ns, using C/A–code only.

VI. EXPERIMENTAL ASSESSMENTS OF THE PRECISION

If the data points are regularly spaced, we can use the time–domain stability measures $\sigma_y(\tau)$, mod$\sigma_y(\tau)$, and $\sigma_x(\tau)$[26]. Applied to a time link, mod$\sigma_y(\tau)$ allows the characterization of the types of noise that are present. In the case of white noise phase modulation (PM), the value of $\sigma_x(\tau)$ for the data spacing is the standard deviation of the white noise, which directly gives the measurement uncertainty. $\sigma_y(\tau)$ allow us to estimate the frequency stability with which clocks can be compared.

In practice it appears that, for intercontinental links without ionospheric measurements and precise ephemerides applied, the white noise phase modulation can be identified for averaging times up to about 3 days, but is not the dominant source for times of one day and over when both corrections are applied. For a single intercontinental common view not corrected for ionospheric measurements and precise ephemerides, uncertainty given by this method is 16 ns. With both corrections applied, the uncertainty of a single measurement reaches 3–4 ns, and decreases to 2 ns when averaging several measurements over a period of one day[27].

Another way to estimate the precision of the common–view measurements is from the standard deviation of the residuals to the smoothed values. This is strictly correct if the smoothing has removed only the measurement noise. For short distance links up to 1000 km, where there is no need to apply ionospheric measurements and precise ephemerides, and for the stations having most accurate coordinates, these standard deviations range from 2 ns to 3 ns. For long distance links with accurate coordinates, but without applying ionospheric measurements and precise ephemerides, standard deviations range from 7 ns to 12 ns; with these two corrections applied standard deviations are of about 3 ns[23,27].

It should be noted that such a precision of measurements makes it possible to access the true performance of the best clocks presently available: by averaging a few measurements over one day, a frequency stability of two or three parts in 10^{14} is realized for the link between two clocks.

VII. EXPERIMENTAL ASSESSMENTS OF THE ACCURACY

A partial test of the accuracy of GPS common–view time transfer is provided by the so–called closure around the world. Totally independent checks are provided by the comparison of GPS with other available techniques of accurate time transfer.

VII.1. CLOSURE AROUND THE WORLD

A partial estimation of the accuracy is attained by using three intercontinental links encircling the Earth to establish the closure condition: the three independent time links should add to zero[23]. However the symmetry of this condition hides possible inaccuracies in the participating links due to lack of calibration, wrong calibration of GPS time equipment, or seasonal changes in receiver delays due to variations of temperature. The experiment involved three laboratories, the OP in Paris, the CRL in Tokyo and the NIST in Boulder. All three laboratories used with codeless ionospheric measurement equipment and had ground–antenna coordinates expressed in the ITRF reference frame with uncertainties ranging from 10 cm to 50 cm. The experiment was conducted over 13 months and is described in detail in [27]. Figure 1 gives the final results. We observe a bias of several nanoseconds which varies with time. The origin of this bias is not understood. It may result from the use of a particular set of precise ephemerides, from ionospheric measurements which are not sufficiently accurate, from tropospheric modelling which is not sufficiently accurate, from combination of these factors or from other causes not understood.

VII.2. COMPARISON WITH TWO–WAY TIME TRANSFER

The Two–Way Satellite Time Transfer (TWSTT) technique has been developed for point–to–point time transfer at the level of several hundreds of picoseconds in precision and accuracy. While the white noise phase modulation of a GPS time comparison is smoothed out when averaging over one– or several– days of common–view data, depending on the distance and the clocks compared, the TWSTT white noise phase modulation is removed over 2 minute averaging time. TWSTT thus presents the great advantage of giving a precise comparison value in real–time.

For about one year the time scales UTC(OCA) at Grasse, France, and UTC(TUG) at Graz, Austria, separated by about 800 km, were compared by means of GPS common–view and Two–Way Satellite Time Transfer[28]. The GPS ground–antenna coordinates at both sites were expressed in the ITRF reference frame with uncertainties of 10 cm. At the end of the experiment, both links were independently calibrated by measuring the differential delays of the GPS receivers and the differential delays of the satellite Earth stations. These calibration were performed by transporting of one GPS receiver and one satellite terminal to the other site. The results obtained by the two methods differ by about 3 ns, but reveal a seasonal variation of about 8 ns (Fig. 2) which, most likely, is mainly the result of temperature–dependent delays in the GPS receiving equipment used.

VII.3. COMPARISON WITH GLONASS

For about 3 months a caesium atomic clock at the BIPM in Sèvres, France, and a hydrogen maser at the VNIIFTRI in Mendeleevo near Moscow, Russia, were compared by GPS common views and GLONASS common views[29]. The two sites are separated by about 3000 km. GPS ground–antenna coordinates were expressed in the ITRF reference frame with uncertainty of 30 cm at the BIPM and 70 cm at the VNIIFTRI. GLONASS ground–antenna coordinates were expressed in the SGS 85 reference frame with uncertainty of about 5 m at each site. The GPS and GLONASS time equipment at each site were differentially calibrated. The results of the experiment are given by Figure 3. We note that the GPS and GLONASS results differ by a fairly constant bias with peak–to–peak discrepancy of about 40 ns. The mean of these differences over the duration of the experiment is 32 ns. The root mean square of the residuals to the mean, which is taken as an estimation of the confidence of the mean is, 13 ns.

The bias of 32 ns between the GLONASS common views and the GPS common views arises partially from an approximation in the calibration of the GLONASS equipment and partially from the large error in the GLONASS ground–antenna coordinates. The noise affecting the GLONASS common views is also partially due to coordinate error, to the absence of a tropospheric correction and to an imprecise estimate of the ionospheric correction. The estimated precision and accuracy of the GPS common-view link is 3 ns to 4 ns.

VII.4. COMPARISON WITH LASSO

The LASSO is a laser technique which should allow the comparison of remote atomic clocks with precision and accuracy of 100 picoseconds or better. The first successful time transfer using LASSO was carried out between the OCA in France and the McDonald Observatory in Texas. At the same time, GPS common-view time transfer was organized between these two sites [30]. The estimated precision and accuracy of GPS time link, after differential calibration of GPS time equipment, is several nanoseconds. Figure 4 shows the comparison between two techniques. We observe a bias of about 192 ns, which is certainly due to non-calibration of the laser equipment. This calibration is being performed and the results should be known soon.

Although LASSO, because of its sensitivity to weather conditions, is inherently unsuited for operational duties, it is certainly an excellent tool for the assessment of the accuracy of GPS, GLONASS and Two-Way time transfers.

VIII. CONCLUSIONS

The use of GPS for time and frequency transfer demonstrates the outstanding potential of this system. The permanent operation, world-wide coverage, low equipment cost and fully automatic reception make GPS the most effective system for time and frequency comparisons. During the last five years, the performance of this technique has been improved by a factor of 10.

For time metrology applications the use of ultra-precise ground-antenna coordinates is necessary. In addition, for intercontinental links, measurements of ionosphere and precise ephemerides must be used. With receiving equipment commercially available at present, the precision of a single GPS common view is 3–4 ns for continental and intercontinental links. This precision drops down to 2–3 ns for integration times of 1 day and longer. For the same integration times, frequency differences between atomic clocks are measured at the level of two or three parts in 10^{14}.

The accuracy of GPS common-view time transfer can be estimated at several nanoseconds and is severely limited by the changes in the delays of the analogue C/A-code receivers, developed in the early 1980s.

To meet the challenge of sub-nanosecond GPS common-view time transfer, required by the upcoming generation of clocks, some of the issues to be addressed are:

* Use of accurate digital P-code receivers[31].
* Use of ultra-precise ephemerides.
* Improvement of measurements of the ionospheric delay.
* Improvement of the estimation of the tropospheric delay[10,11].

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List of Acronyms and Abbreviations

AS	Anti–Spoofing
BIPM	Bureau International des Poids et Mesures, Sèvres, France
CRL	Communications Research Laboratory, Tokyo, Japan
CV	Common View
DMA	Defense Mapping Agency
GLONASS	Global Navigation Satellite System (Globalnaya Navygatzyonnaya Sputnikovaya Systema)
GPS	Global Positioning System
IERS	International Earth Rotation Service
IGS	International Geodynamic Service
ITRF	IERS Terrestrial Reference Frame
LASSO	Laser Synchronization from Satellite Orbit
MJD	Modified Julian Day
NBS	National Bureau of Standards
NGS	National Geodetic Survey, Rockville, Maryland
NIST	National Institute of Standards and Technology, Boulder, Colorado
OP	Observatoire de Paris
OCA	Observatoire de la Côte d'Azur, Grasse, France
SA	Selective Availability
SGS	Soviet Geocentric System
TAI	International Atomic Time
TUG	Technical University Graz, Graz, Austria
TWSTT	Two–Way Satellite Time Transfer
UTC	Universal Coordinated Time
UTC(i)	Universal Coordinated Time as realized by laboratory i
VNIIFTRI	Russian National Time & Frequency Service, Mendeleevo, Russia
WGS	World Geodetic System

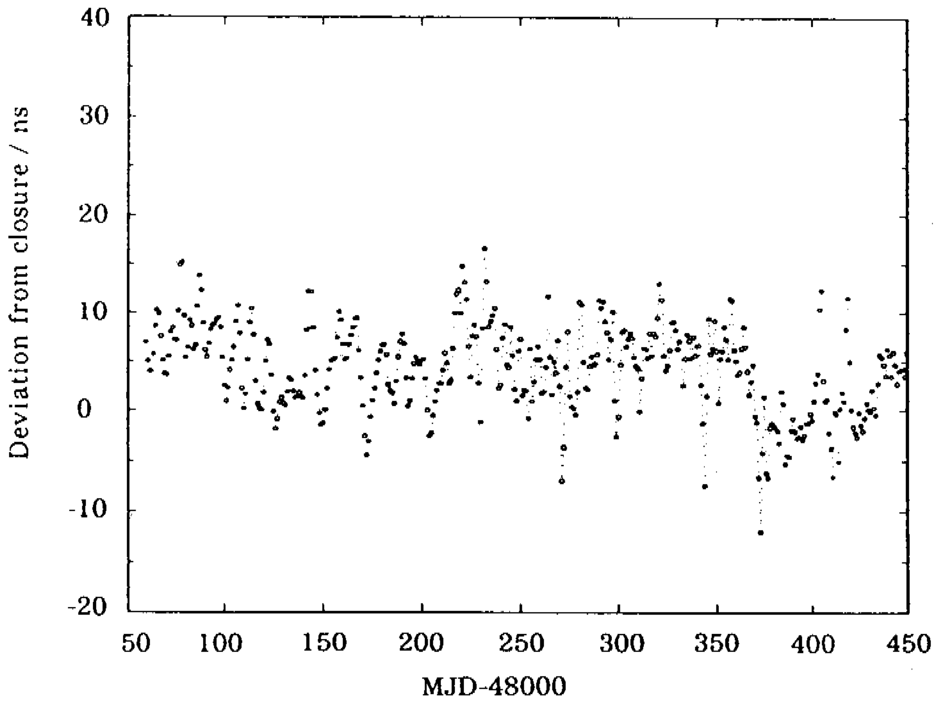

Figure 1. Deviation from closure around the world via OP, NIST and CRL with data corrected using measured ionospheric delays and DMA precise ephemerides.

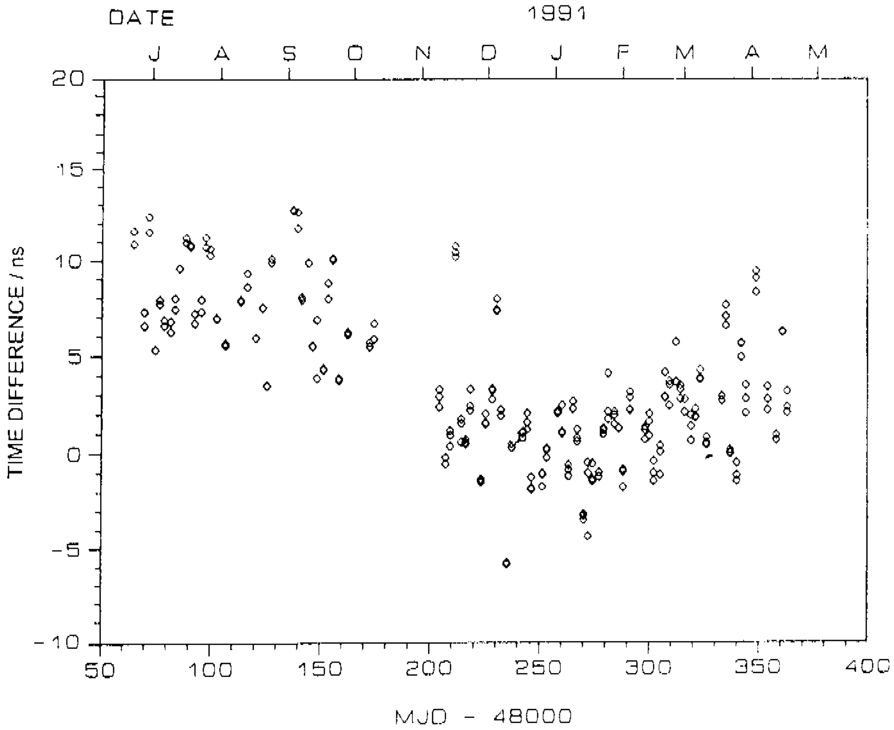

Figure 2. Difference between [UTC(TUG) - UTC(OCA)] obtained by Two-Way measurements and [UTC(TUG) - UTC(OCA)] obtained by GPS common-view measurements.

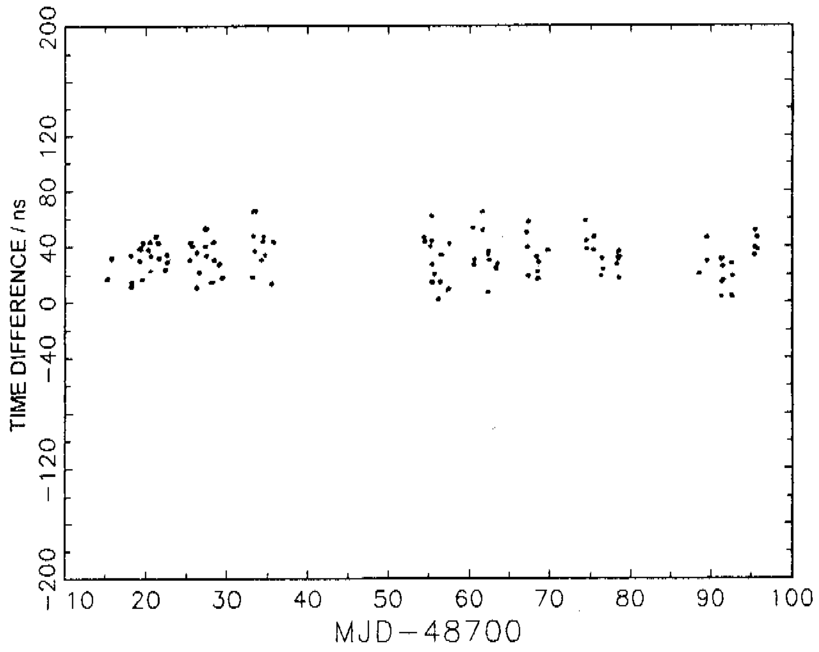

Figure 3. Difference between [BIPM Cs Clock - VNIIFTRI H Maser] obtained by Two-Way measurements and [BIPM Cs Clock - VNIIFTRI H Maser] obtained by GPS common-view measurements.

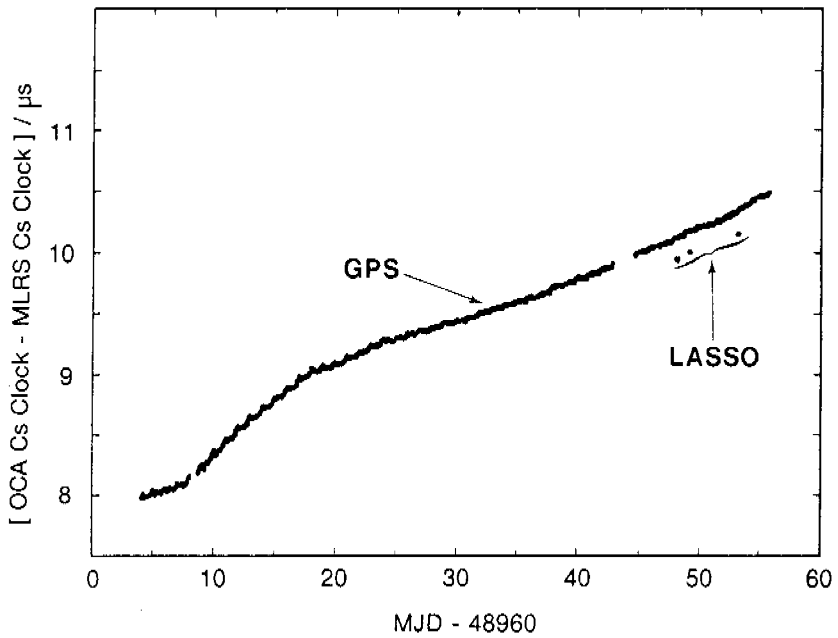

Figure 4. [OCA Cs Clock - MLRS Cs Clock] obtained by GPS common-view measurements and by LASSO.

QUESTIONS AND ANSWERS

Richard Sarrica, Hewlett–Packard: On your GPS temperature plot, what was that actually the temperature measurements of? Was that satellite temperatures?

W. Lewandowski: No, it was just the external temperature of the laboratory. You know, just simple temperature outside the laboratory, near the antenna. We have done this for other status comparing to receivers. This is a very rough comparison. But it shows this immediate effect.

Richard Sarrica: So temperature affects the electronics of the system?

W. Lewandowski: The antenna, maybe the bandpass filters in the antenna. We don't understand the principal of the effect. We have discussed this with the manufacturers. And only some of the receivers are affected by this. All are affected at the level of one ns, I believe. But some have a huge effect of temperature, as big as two ns per degree Celsius of value. They are very expensive thermometers.

Richard Sarrica: So the hope is that once those are characterized, you can then subtract those out also.

W. Lewandowski: To subtract this – one can try to model this and to subtract, but I believe it is not the way to do it.

Harrison Freer, GPS NASA Control Station: You made mention of modeling the troposphere and it relates to this question; and you mentioned temperature as one of the variables you looked at. Have you looked at the other variables, humidity and those kinds of things, to again model tropospheric differences in your process?

W. Lewandowski: Tropospheric modeling was, as I said before, not yet well addressed. And we will have during this meeting a paper by Dr. Kirchner on this; and I expect that this will the first item in trying to resolve this problem.

David Allan, Allan's Time: I wish to comment further on this temperature effect. It is not conclusive at all and it is still being investigated. But it seems that those receivers which down convert and send an IF signal down have less temperature effect than those which send the direct RF signal down. But we don't know for sure. Those are just some of the first experimental data.

W. Lewandowski: Yes, and especially NBS–type receivers which we always use down convert this one frequency; and they are less sensitive to temperature. The time receivers which were transformed from geodetic receivers to time receivers, in general they don't down convert their one frequency and they are sensitive to temperature. But that is not conclusive. I would not like to say that all of them do this. But we observed this in our practice.

Claudine Thomas, BIPM: I have one more comment. You spoke about the technical directives of GPS receivers. This has been accepted in Metrologia and will be published in the next issue in January of next year, Volume 31. Everyone can get it. It is signed by the chairman of the group who is Dave Allan, and also by the secretary.