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GPS TIME CLOSURE AROUND THE WORLD USING PRECISE EPHEMERIDES, IONOSPHERIC MEASUREMENTS AND ACCURATE ANTENNA COORDINATES.

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ABSTRACT

Over intercontinental distances the accuracy of Global Positioning System (GPS) time transfers ranges from 10 to 20 ns. The principal error sources are the broadcast ionospheric model, the broadcast ephemerides and the local antenna coordinates.

Previous work has already shown the impact of the use of measured ionospheric delays as provided by dual frequency codeless ionospheric measurement systems. The role of precise GPS satellite ephemerides, now available from the US Defense Mapping Agency (DMA), has already been investigated. The improvement brought by the corrections to local GPS receiver antenna, resulting from the BIPM differential positioning method, has also been demonstrated for short-distance time comparisons.

At present, ionospheric measurement systems of the type designed by the National Institute of Standards and Technology (NIST) operate on a regular basis at the NIST in Boulder (Colorado, USA) and at the Paris Observatory (OP) in Paris (France), and systems of the type designed by the Communications Research Laboratory (CRL) operate at the CRL in Tokyo (Japan). Broadcast ephemerides are currently recorded in Mojave (California, USA) and at the BIPM (France). The GPS antenna coordinates of OP, NIST and CRL are now unified in IERS Terrestrial Frame. In this paper, we realize for the first time the closure around the world obtained by the combination of time transfers OP-NIST, NIST-CRL and CRL-OP after reduction of the three major error sources. It gives the evidence of improvement in accuracy for GPS time transfer with using precise ephemerides, measured ionospheric delays and accurate antenna coordinates.

INTRODUCTION

The excellence of worldwide time unification depends on the quality of the clocks kept by national timing centers and on the means of time comparisons. Rapid development of the Global Positioning System since 1983 has led to major improvements in the precision and accuracy of time metrology. Using commercially available C/A Code* GPS time receivers, time comparisons can easily be performed with an accuracy of 10 to 20 nanoseconds over intercontinental distances. However, it should be possible to improve this performance by removal of residual systematic errors [1]. In GPS time transfers, the three principal sources of error are the local antenna coordinates, the broadcast ionospheric model and the broadcast ephemerides. Previous work shows the effect of correcting these errors individually [2] [3] [4]. We present here a five-month experiment in which three long-distance time links are performed with simultaneous reduction of these error sources. The laboratories involved are the Paris Observatory (Paris, France), the National Institute of Standards and Technology (Boulder, Colorado, USA) and the Communications Research Laboratory (Tokyo, Japan). Closure around the world is obtained by combination of these time links: since the closure leads in principle to a zero sum, we have a clear test of accuracy for overall GPS time transfer.

1. THE EXPERIMENT

The three long-distance time transfers UTC(OP) - UTC(NIST), UTC(NIST) - UTC(CRL) and UTC(CRL) - UTC(OP) were computed using the common-view method [5], for a 162-day period, from 1990 June 16 (MJD 48058) to 1990 November 24 (MJD 48219).

The GPS data taken at the three sites correspond to the International Schedule N°15, issued by the Bureau International des Poids et Mesures, and implemented on 1990 June 12 (MJD 48054). This schedule includes Block I and Block II satellites. For one part of the period under study (1990 June 16 to 1990 August 10), the intentional degradation of GPS signals, known as Selective Availability (SA), was turned on for Block II satellites. It can be shown however that it affected only the satellite clocks, producing a phase jitter which is completely removed by strict common views [6].

In our experiment only common views with the same starting time and the same track length are kept. Time comparison values UTC(Lab1) - UTC(Lab2) are obtained for each observed satellite at the time, T_{mid}, of the midpoint of the track.

At the time of the experiment some satellites were in their rephasing manoeuvre. In consequence, their elevations were sometimes too low to be observed from one of the sites although, in principle, they formed part of the international Schedule.

The GPS receivers used at OP and NIST come from the same maker and use the same software to treat the short-term data. This enhances the symmetry of the experiment for the time link OP-NIST. This is not the case for the NIST-CRL and CRL-OP links, the GPS receiver in regular operation at CRL coming from another maker. Detailed characteristics of the three time links are given in Table 1.

TABLE 1: *Time links OP-NIST, NIST-CRL and CRL-OP.*

	OP-NIST	NIST-CRL	CRL-OP
Baseline	7388km	8522km	8816km
CV/day	9	7	8
p	61%	62%	48%

- * *CV/day gives the number of scheduled common-view tracks by day for each pair of laboratories*
- * *p gives the fraction of scheduled tracks for the period of study (162 days) which correspond to perfect common views and which could simultaneously be corrected for antenna coordinates, measured ionospheric delay and precise ephemerides.*

Before analysing the results of this experiment, we review the methods for reducing the three main sources of errors: antenna coordinates, broadcast ionospheric model and broadcast ephemerides [7].

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* *Acronyms are listed at the end of the text.*

1.1 ACCURATE ANTENNA COORDINATES

Accurate antenna coordinates can be determined with uncertainties of a few centimeters using geodetic methods to obtain [8] the relative position of the antenna with respect to the nearest IERS site. The BIPM has also developed a method of differential positioning between GPS antennas using the data of the time comparisons themselves [2]. The consistency of the coordinates obtained by this method is within 50 cm for distances up to 1000 km. By combining these techniques, all national laboratories equipped with GPS receivers have, over the last few years, been linked to IERS sites [9]. On 1990 June 12 at 0h00 UTC (MJD 48054), as suggested by the BIPM, these corrected coordinates were introduced into the GPS time receivers, ensuring worldwide homogeneity of the coordinates in the IERS Terrestrial Reference Frame (ITRF).

Thus, at the beginning of our experiment, the OP antenna coordinates were known with an uncertainty of 50 cm. They were obtained, by the BIPM differential positioning method, with respect to the Grasse ITRF SLR site from data covering the period 1987 December 15 to 1988 June 21 [2]. For the NIST, the GPS antenna has coordinates known with an uncertainty of 30 cm. These were obtained by GPS geodetic differential positioning with respect to the Platteville VLBI site on July 1989 [8]. The CRL antenna coordinates are known to within 10 cm, relative to the Kashima VLBI site, by local survey on March 1989 [10].

1.2 MEASURED IONOSPHERIC DELAY

In the usual GPS data files, the correction used for ionospheric refraction comes from a model [11], the parameters of which are included in the GPS message. At radio frequencies, however, the ionosphere is a dispersive medium so its effect on time comparison between local and GPS satellite clocks can be estimated by dual-frequency methods. Dual-frequency receivers, which do not depend on knowledge of the P-Code, have recently been developed [12] [13]. They give measurements of ionospheric delay along the line of sight of satellites with uncertainties of 1 to 2 ns [14]. The gain in precision for long-distance time comparisons has already been demonstrated when the two branches of the link are corrected with measured ionospheric values [15]. The gain in accuracy was also confirmed by the study of the closure around the world via NIST, OP and CRL through the use of such measurements [3].

The OP and NIST are equipped with similar dual-frequency GPS receivers of the NIST type [13] (NIST Ionospheric Measurement System). In their present configuration, these devices give values of ionospheric delay for all satellites in view every 15 seconds. These data are stored after a linear fit over 15 minutes at a time corresponding to round quarters of hours: 0h00 UTC, 0h15 UTC, 0h30 UTC, etc.

The CRL is equipped with another type of dual-frequency GPS receiver designed by the CRL [12] (Realtime TECmeter). This device has a single channel and is programmed to observe by priority the satellites suggested by the BIPM International Schedule. It operates with 4-minute sequences: about 1 minute to point its directional antenna and about 3 minutes to perform the observation. Values of the ionospheric delay are taken every 6 seconds for a given scheduled satellite. The mean and the standard deviation of these data are provided for the mid-point of the observation sequence.

From the ionospheric data provided by one or another device are made estimates of the value of the measured ionospheric delay for the mid-point (T_{mid}) of a given 13-minute track of satellite s. To do this, we use several measurements for the same satellite s, surrounding T_{mid}. A polynomial fit is then performed (linear to cubic depending on the number of values used). The estimated value at T_{mid} is deduced by interpolation and is used to correct UTC(Lab) - GPS time. This polynomial fit is never extrapolated and measurements from other satellites are never used.

1.3 PRECISE EPHEMERIDES

The GPS precise ephemerides were computed at the U.S. Naval Surface Warfare Center (NSWC) from the beginning of 1986 to 1989 July 29. Since then they have been produced by the Defense Mapping Agency (DMA). These ephemerides are received on a regular basis at the BIPM. Their estimated accuracy is of order 3 meters. At present, the delay of access to precise ephemerides is about two months, so the period we study here is limited to mid-November 1990.

In practice, computations with precise ephemerides require knowledge of the broadcast ephemerides used, during the observation, by the receiver software in order to apply differential corrections [4]. To perform the closure around the world it is necessary to have access to recorded broadcast ephemerides on at least two sites correctly situated in the world. The BIPM started the regular collection of GPS broadcast ephemerides in May 1990. For this experiment, these data were used together with broadcast ephemerides recorded in Mojave (California, USA) by the U.S. National Geodetic Survey (NGS).

The precise ephemerides, PE_i, are provided in cartesian coordinates (expressed in WGS 84 reference frame) at time T_i corresponding to round quarters of hours: 0h00 UTC, 0h15 UTC, 0h30 UTC etc. It is then necessary to compute, from the broadcast Keplerian elements of satellite s, its positions BE_1, BE_2 and BE_3 for three times T_1, T_2 and T_3, such that:

$$T_1 < T_{start} < T_2 < T_{stop} < T_3$$

where T_{start} and T_{stop} are the starting time and the stopping time of the usual 13-minute tracking. The ephemeride corrections $PE_i - BE_i$, for i = 1,2,3, are transformed in a frame linked to the satellite (On-track, Radial, Cross-track) and a quadratic polynomial in time is computed to represent each component. A quadratic representation is also computed in the same frame for the vector satellite-station. The inner product of these quadratic representations provides the corrections to GPS measurements each 15 seconds. A linear fit over 13 minutes on these short-term corrections gives the correction at the middle-time T_{mid} of the track.

1.4 COMBINING THE DATA

Data files of measured values UTC(Lab) - GPS time and of ionospheric measurements for the three laboratories involved, as well as data files of precise ephemerides produced by the DMA and broadcast ephemerides from Mojave and Paris, were gathered at the BIPM for processing. Only the tracks corresponding to perfect common views, which could be simultaneously corrected for ionospheric model and precise ephemerides (see last line of Table 1), were retained. The results given in Sect. 2 involve only the values UTC(Lab1) - UTC(Lab2) corresponding to these particular trackings, whether the tracks include the corrections or not.

2. RESULTS

The gain in precision from the simultaneous use of corrected antenna coordinates, ionospheric measurements and precise ephemerides has already been demonstrated for an observation period of 67 days for the time link UTC(OP) - UTC(NIST) [7]. We present here similar results for a longer period and for three time links. We then analyse the results concerning the closure around the world.

2.1. PRECISION OF TIME COMPARISONS

The corrections to the antenna coordinates being already introduced, four different cases may be distinguished for each pair of laboratories:

- non-corrected values
- values corrected for ephemerides only
- values corrected for ionosphere only
- values corrected for both ephemerides and ionosphere.

For each case, a Vondrak smoothing [16] is performed on the values UTC(Lab1) - UTC(Lab2). The standard deviations of the residuals to the smoothings for the complete period under study are given in Table 2. The smoothing used acts as a low-pass filter with a cut-off period of about 3 days.

TABLE 2: *Standard deviation, in nanoseconds, of the residuals to the smoothed values UTC(OP) - UTC(NIST), UTC(NIST) - UTC(CRL) and UTC(CRL) - UTC(OP) for the whole period under study, with application or not of the corrections.*

	OP-NIST	NIST-CRL	CRL-OP
non corrected	9,7	15,4	10,4
ephem. only	8,9	8,9	8,1
iono. only	5,9	12,3	6,7
ephem. + iono.	4,3	4,5	4,6

Application of individual corrections decreases the total standard deviation, for each link, with a clear improvement when both corrections are applied simultaneously. This improvement is linked to the length of the baselines involved. For such long baselines, common-view observations are mostly at low elevations and so are more sensitive to ionospheric effects and to satellite positions.

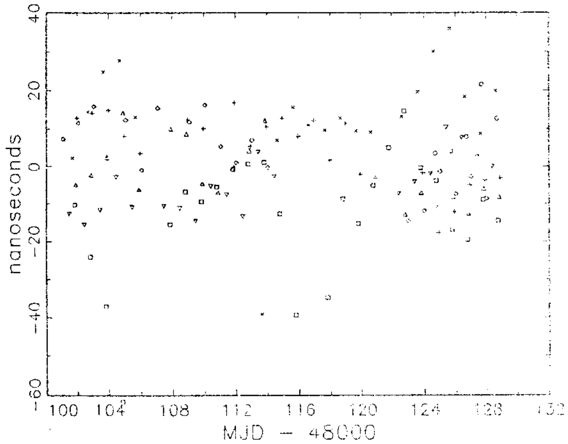

FIGURE 1: *GPS time transfer UTC(NIST) - UTC(CRL): residuals to the smoothed non-corrected values (a different symbol is used for each track).*

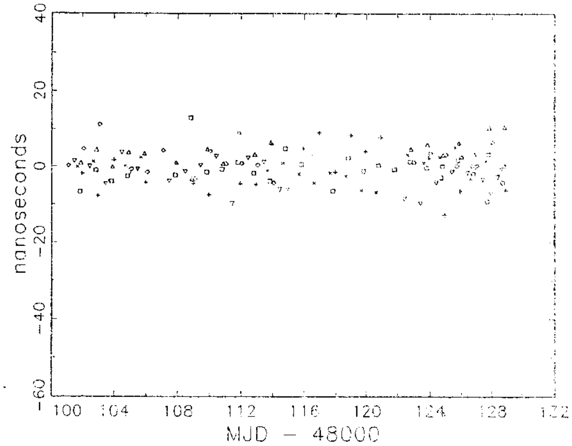

FIGURE 2: *GPS time transfer UTC(NIST) - UTC(CRL): residuals to the smoothed values previously corrected for precise ephemerides and measured ionospheric delays.*

The residuals to the smoothed values UTC(NIST) - UTC(CRL) for each data point of a given period of the experiment are presented in Figs. 1 and 2. Comparison of these figures shows the improvement of precision in the determination of UTC(NIST) - UTC(CRL) when the error sources are corrected simultaneously. The daily standard deviations of the residuals drop to values around 4 ns (see Fig. 3).

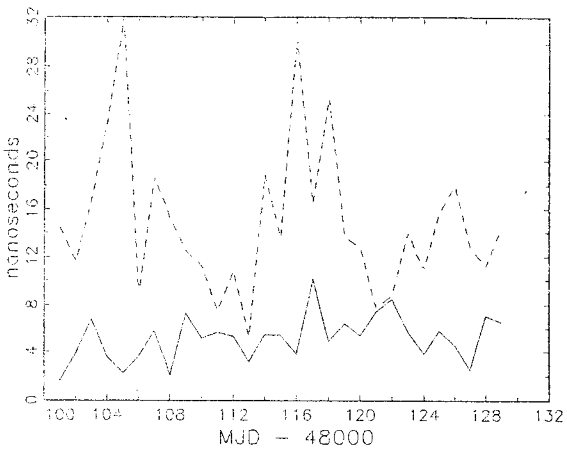

FIGURE 3: *GPS time transfer UTC(NIST) - UTC(CRL): daily standard deviations of the residuals obtained with:*

– – – – – – non-corrected data,

———— data corrected for precise ephemerides and measured ionospheric delays.

Another example of the improvement in precision is given in Fig. 4 and concerns the time link OP-NIST in July-August 1990. The residuals to smoothed values of UTC(OP) - UTC(NIST) are shown for only one daily common view corresponding to satellite 12. With non-corrected data, satellite 12 presented very large residuals for some days in August. This effect completely disappears only when corrections for precise ephemerides are applied and was thus linked to very poor broadcast ephemerides. In general, the use of precise ephemerides helps to smooth the daily residuals for each common-view track while the use of ionospheric measurements tends to decrease the biases between satellites [7]. These two effects combine to reduce the uncertainty of the time comparison.

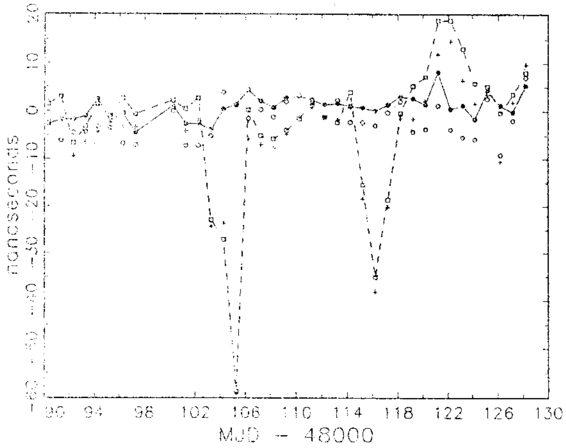

FIGURE 4: *GPS time transfer UTC(OP) - UTC(NIST): residuals to the smoothed values for one daily common-view track (satellite 12).*

–□–□–□–□–□ non-corrected data,

–○–○–○–○–○ data corrected for precise ephemerides only,

+ – + – + – + data corrected for ionosphere only,

–◆–◆–◆–◆ data corrected for precise ephemerides and ionosphere.

Daily values of UTC(CRL) - UTC(OP), at 0h00 UTC, were estimated from the smoothed data points. The Allan deviation of these daily non-corrected and corrected values is given in Figs. 5 and 6 with a basic sample duration equal to one day. It is impossible to estimate the Allan deviation on a shorter evenly-spaced time interval since the scheduled common views CRL-OP are spread over 11 hours each day.

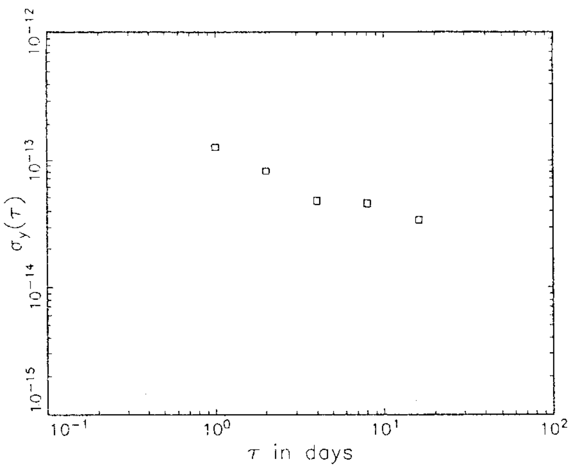

FIGURE 5: *GPS time transfer UTC(CRL) - UTC(OP): Allan deviation of the non-corrected values.*

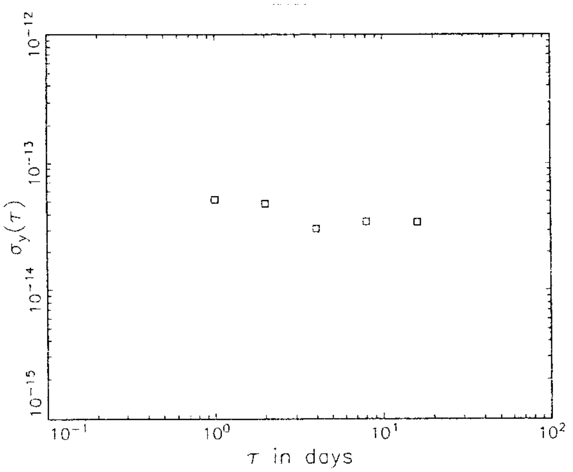

FIGURE 6: *GPS time transfer UTC(CRL) - UTC(OP): Allan deviation of the corrected values for precise ephemerides and ionosphere.*

Raw data are affected by white phase noise whose origin is the time difference measurements. It is smoothed out by averaging over 5 to 6 days. When corrections for precise ephemerides and measured ionospheric delays are applied, the measurement noise is already smoothed out when averaging over one day. The real performance of the local clocks, white frequency modulation for that averaging time, is then accessible to examination.

2.2. ACCURACY TEST: CLOSURE AROUND THE WORLD

A test of accuracy for GPS time transfer can be performed by computing the closure around the world via OP, NIST and CRL. Daily values of UTC(OP) - UTC(NIST), UTC(NIST) - UTC(CRL) and UTC(CRL) - UTC(OP) were estimated from the smoothed data points (the Vondrak smoothing was performed with the same smoothing degree for each time link). The resulting daily values of the deviation from closure, for the whole period under study, are shown in Fig. 7 without correction and in Fig. 8 with corrections applied. Fig. 8 provides evidence of a gain in accuracy when all three long-distance time links are computed using the corrections for precise satellite ephemerides and measured ionospheric delays.

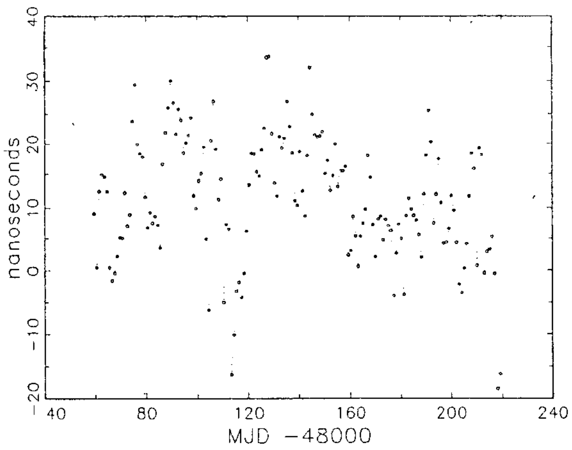

FIGURE 7: *Deviation from closure around the world via OP, NIST and CRL with non-corrected GPS data.*

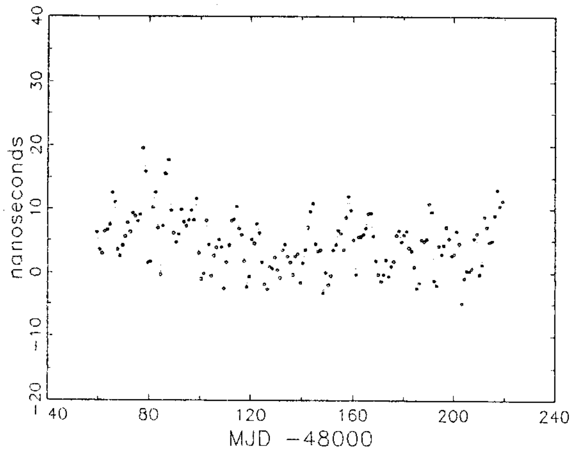

FIGURE 8: *Deviation from closure around the world via OP, NIST and CRL with GPS data corrected for precise ephemerides and measured ionospheric delay.*

To analyze the closure results in detail, Allan deviations were computed with and without corrections and plotted in Figs. 9 and 10. The figures exhibit common behaviour for the Allan deviation as a function of the inverse of the averaging time. The noise is lower when corrections are applied. It should be noted that the bending for $\tau < 2$ days is due to the smoothing that was applied on individual time links and has no physical interpretation.

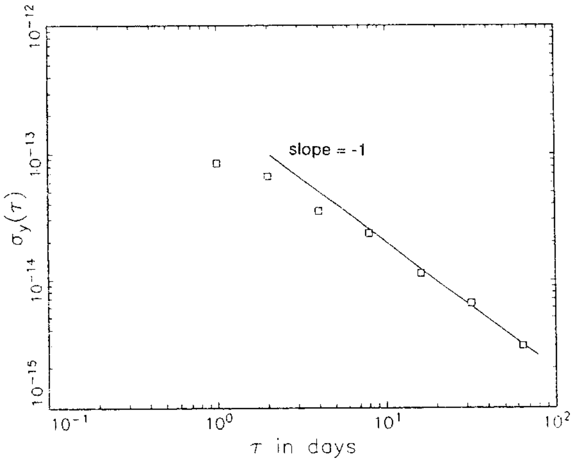

FIGURE 9: *Square root of the Allan variance of the deviations from closure obtained with non-corrected data.*

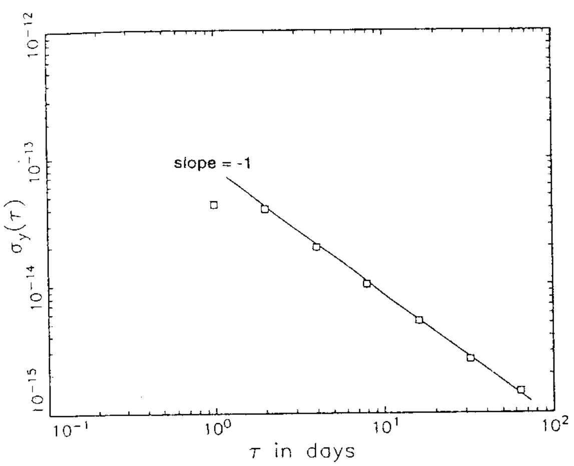

FIGURE 10: *Square root of the Allan variance of the deviations from closure obtained with data corrected for precise ephemerides and measured ionospheric delay.*

Use of the modified Allan variance (Figs. 11 and 12) allows us to characterize the noise affecting the values of the deviation from closure. Non-corrected data exhibit flicker phase noise. When corrections are applied, the flicker phase noise is not present and the obtained values, for the closure, then exhibit white phase noise up to an averaging time of about 20 days. This justifies computation of mean values of the deviation from closure for periods of duration up to 20 days and corresponding standard deviations.

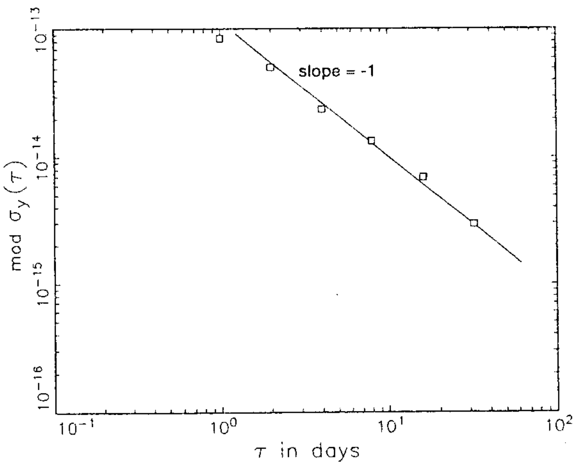

FIGURE 11: *Square root of the modified Allan variance of the deviations from closure obtained with non-corrected data.*

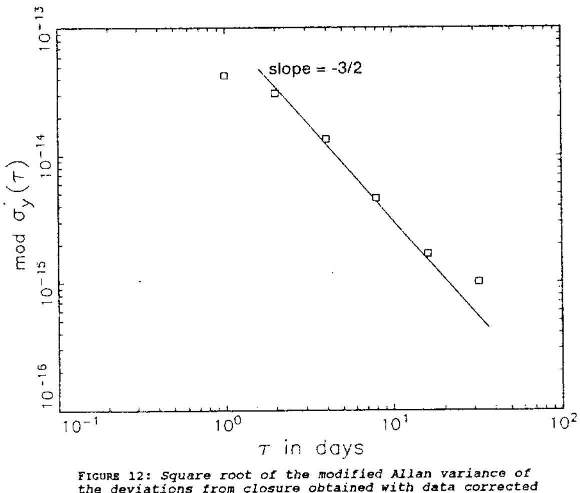

FIGURE 12: *Square root of the modified Allan variance of the deviations from closure obtained with data corrected for precise ephemerides and measured ionospheric delay.*

For 20-day averaging period the results are as follows (Table 3):

Table 3: *Mean values of the deviation from closure around the world estimated by the quantity [UTC(OP) - UTC(NIST)] + [UTC(NIST) - UTC(CRL)] + [UTC(CRL) - UTC(OP)] and standard deviations.*

Averaging period (MJD)	Mean deviation from the closure (ns)	Standard deviation (ns)
48059-48078	7,9	1,0
48079-48098	8,1	1,0
48099-48118	3,6	0,8
48119-48138	2,1	0,6
48139-48158	4,1	1,0
48159-48178	4,0	0,8
48179-48198	3,9	0,8
48199-48218	4,1	1,0

Table 3 shows a residual systematic effect of a few nanoseconds. Such a bias may be attributed to residual errors in antenna coordinates. The geographical positions of the involved sites necessitate that the useful common views are observed from one site for privileged directions. This keeps the coordinate errors from averaging and could produce a systematic bias.

Another point of interest is that the mean value of the closure depends on the period over which it is estimated. This may arise from the use of precise ephemerides which are not computed in a reference frame consistent with the IERS Terrestrial Reference Frame. This would introduce rotations of the reference frame of the precise ephemerides which would induce slowly varying shifts in the closure values. It might be possible to correct the precise ephemerides for this effect; further investigation of this topic is in progress at the BIPM.

Finally, one other phenomenon that could contribute to the bias in the closure is a systematic error due to the ionospheric measurements [14]. This probably depends on ionospheric conditions, in particular on whether observations are taken by day or by night. This would affect values of the deviation from closure obtained through time links having baselines long enough that one of the lines of sight corresponds to day-time while the other one corresponds to night-time. Such a bias will slowly evolve as the dates of observation change due to the sidereal orbits of satellites.

CONCLUSIONS

A five-month study of the GPS time transfers OP-NIST, NIST-CRL and CRL-OP shows that the consistency of long-distance GPS time comparisons is greatly improved through use of accurate antenna coordinates, precise satellite ephemerides and measured ionospheric delays. At the precision achieved with reducing these error sources, local time scales can be fully compared for averaging times of the order of one day. This performance matches with that observed for short-distance time comparisons [1].

The computation of the closure around the world via OP, NIST and CRL shows that corrections for precise satellite ephemerides and measured ionospheric delays greatly improve the accuracy of GPS time transfers. A slowly varying bias, of the order of a few nanoseconds, remains and is the subject of further investigations.

The GPS has proved to be an efficient tool for long-distance time comparison at the nanosecond-level both in precision and accuracy. At present, GPS is better than any existing system or method; yet this performance is still open to improvement with better conditions of operation: improved precise ephemerides, improved precise antenna coordinates, improved measurements of ionosphere, calibration of GPS receivers, unification of receiver software, control of multipath propagation, use of Earth tides model *etc.* The implementation of SA would be a severe drawback in terms of direct access to time, but its effects could be partially or completely removed for accurate time comparisons.

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ACRONYMS

BIPM	Bureau International des Poids et Mesures
C/A Code	Coarse/Acquisition Code
CRL	Communications Research Laboratory
CV	Common View
DMA	Defense Mapping Agency
IERS	International Earth Rotation Service
ITRF	IERS Terrestrial Reference Frame
LPTF	Laboratoire Primaire du Temps et des Fréquences
MJD	Modified Julian Date
NIMS	NIST Ionospheric Measurement System
NIST	National Institute of Standards and Technology
NGS	National Geodetic Survey
NSWC	Naval Surface Warfare Center
OP	Observatoire de Paris
P-Code	Precision Code
SLR	Satellite Laser Ranging
VLBI	Very Long Baseline Interferometry
WGS	World Geodetic System

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