THE USE OF PRECISE EPHEMERIDES, IONOSPHERIC DATA AND CORRECTED ANTENNA COORDINATES IN A LONG–DISTANCE GPS TIME TRANSFER

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Abstract

Over intercontinental distances the accuracy of 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 correcting each of these error sources individually, using either measured ionospheric delays, precise GPS satellite ephemerides, or improved antenna coordinates. Ionospheric delay measurements can be provided by dual frequency codeless ionospheric calibrators. Precise GPS satellite ephemerides are now available from the U.S. Defense Mapping Agency (DMA), and others. GPS receiver antenna coordinates should be accurately linked to stations of the IERS Terrestrial Reference Frame. If such a link is not available from geodetic methods, accurate differential positioning, between GPS antennas, can be realized over short distances, using the BIPM method.

For the first time, the three major error sources for GPS time transfer can be reduced simultaneously for a particular time link. Ionospheric measurement systems of the NIST type are now operating on a regular basis at the National Institute of Standards and Technology in Boulder (Colorado, USA) and at the Paris Observatory in Paris (France). Broadcast ephemerides are currently recorded for time–transfer tracks between these sites, this being necessary for using precise ephemerides. At last, corrected local GPS antenna coordinates are now introduced in GPS receivers at both sites. This paper shows the improvement in precision for this long–distance time comparison resulting from the reduction of these three error sources.

INTRODUCTION

The excellence of worldwide unification of time depends on the means of time comparison. The rapid development of the Global Positioning System since 1983 has led to a major improvement 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 greatly by removing systematic errors[1]. In GPS time transfers the three principal error sources are the local antenna coordinates, the broadcast ionospheric model and the broadcast ephemerides. Previous work shows the impact of correcting each of these error sources individually[2, 3, 4]. We show here the first example of long–distance time comparison where all three errors may be reduced simultaneously. This experiment concerns the time link between the Paris Observatory (Paris, France) and the National Institute of Standards and Technology (Boulder, Colorado, USA), which corresponds to 7400 km baseline. In following sections the experiment is first presented in detail, then the results are analyzed.

1–THE EXPERIMENT

The difference UTC(OP) – UTC(NIST) is computed using the common–view method[5], for a 67–day period, from 1990 June 14 (MJD 48056) to 1990 August 20 (MJD 48123). The GPS data taken at the two sites correspond to the international GPS schedule n°15, issued by the Bureau International des Poids et Mesures, and implemented on 1990 June 12 (MJD 48054), see table 1.

TABLE 1: Daily scheduled common views between
Europe and West North America (MJD 48054)

PRN	Cl	h	m	El(from OP)	El(from NIST)
14	00	00	16	37	30
13	08	01	36	44	41
13	09	02	08	39	33
3	08	04	16	14	68
16	08	05	36	41	48
12	08	09	20	59	30
20	19	11	28	58	18
2	08	21	04	36	23
14	01	23	44	26	25

Nine tracks, spread over 14 hours, are scheduled each day, four of which correspond to Block I satellites and five to Block II satellites, so we have 603 potential common views for the period under study. However the elevation of satellite 3 was too low from Paris and became observable only at mid–July due to its rephasing maneuver.

For one part of the period under study (1990 June 14 to 1990 August 10), the intentional degradation of GPS signals, known as Selective Availability (SA), was turned on for the 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] (same start time and same track length). In our experiment we found 576 perfect common views. Moreover, the two GPS receivers come from the same maker and use the same software for treating the short–term data. This further helps remove the clock dither and enhances the symmetry of the experiment.

The values UTC(OP) – UTC(NIST) are obtained for each observed satellite at the time, Tmid, of the midpoint of the track.

1–1 ACCURATE ANTENNA COORDINATES

Accurate antenna coordinates can be obtained with uncertainties of a few centimeters through geodetic methods[7] by relative positioning between the antenna and 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. Using these two techniques together, over the last few years, all national laboratories equipped with GPS have been linked to IERS sites. 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 homogenization of the coordinates in the IERS Terrestrial Reference Frame (ITRF).

Thus, at the beginning of our experiment, the NIST GPS antenna has coordinates known with an uncertainty of 30 cm. They were obtained by GPS geodetic differential positioning with respect to Platteville VLBI site in July 1989[7]. For OP, the coordinates were obtained by the BIPM differential positioning method, with respect to the Grasse ITRF SLR site. They are derived from data covering 1987 December 15 to 1988 June 21[2] and are given with an uncertainty of 50 cm.

1–2 MEASURED IONOSPHERIC DELAY

In the usual GPS data file, the correction used for ionospheric refraction comes from a model[8], the parameters of which are included in the GPS message. At radio–frequencies, however, the ionosphere is a dispersive medium so that 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[9, 10]. They give measurements of ionospheric delay along the line of sight of satellites with uncertainties of 1 to 2 ns. The gain in precision for long–distance time comparisons has already been shown when the two branches of the link are corrected with measured ionospheric values[11]. The gain in accuracy was also pointed out from the study of the closure around the world via NIST, OP and CRL through the use of such measurements[3].

The two sites involved in this study are equipped with similar codeless dual–frequency GPS receivers of the NIST type[10] (NIST Ionospheric Measurement System). In their present configuration, these devices are stand–alone units, with values of ionospheric delay for all satellites in view available as often as every 15 seconds. These data are stored after a linear fit over 15 minutes, at times Ti corresponding to round quarters of hours: 0h00 UTC, 0h15 UTC, 0h30 UTC,... etc. From these data it is necessary to estimate the value of the measured ionospheric delay for a given tracking (satellite s and middle–time Tmid). In the general case, we use several measurements for the same satellite s, surrounding Tmid. A polynomial fit is then performed (linear to cubic depending on the number of values which are used). The estimated value is deduced for Tmid by interpolation. This polynomial fit is never extrapolated and measurements from other satellites are never used. If only one value is available for s, it is used only if its reference time, Ti, is less than 7.5 minutes away from Tmid. The ionospheric measure for Ti and the slope of the 15–minute linear fit, computed in the receiver over

15–second ionospheric measurements, are then processed to estimate the ionospheric delay at Tmid.

With the available data from both sites, 393 strict common views were corrected for the ionospheric delay during the period under study.

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 the order of 3 meters. At present time, the delay of access of precise ephemerides is about three months, so that the period we are studying here is limited to the end of August 1990.

In practice, computations with precise ephemerides require knowledge of the broadcast ephemerides used by the receiver software in order to apply differential corrections[4]. The BIPM started the regular collection of GPS broadcast ephemerides in May 1990. Another difficulty is the possible change of ephemeris parameters during the usual 13–minute tracking period. The software of the GPS receivers used in this experiment was modified in order to retain a single ephemeris for the full duration of the tracking. The available ephemerides data collected by the BIPM could be used for correcting 454 strict common views between OP and NIST for the period under study.

The precise ephemerides PEi are provided in Cartesian coordinates at times Ti corresponding to round quarters of hours: 0h00 UTC, 0h15 UTC, 0h30 UTC, 0h45 UTC...etc. It is then necessary to compute from the broadcast Keplerian elements, the positions BE1, BE2 and BE3 for three times T1, T2 and T3, such that:

$$\mathrm{T1} < \mathrm{Tstart} < \mathrm{T2} < \mathrm{Tstop} < \mathrm{T3}$$

where Tstart and Tstop are the start time and the stop time of the usual 13–minute tracking. The ephemeris corrections PEi – BEi, 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 on these short–term corrections gives the correction at Tmid of the values UTC(Lab) – GPS for each laboratory.

2 RESULTS

For the period under study, 314 perfect common views between OP and NIST could be corrected simultaneously with measured ionospheric delays and precise ephemerides. The results given here only involve the values UTC(OP) – UTC(NIST) corresponding to these particular trackings, whether the tracks include the corrections or not.

The corrections to the antenna coordinates being already introduced, four different cases are emphasized in this study:

- raw values,

- corrected values for ephemerides only,
- corrected values for ionosphere only,
- corrected values for ephemerides and ionosphere together.

For each case, a Vondrak smoothing[12] is performed on the values UTC(OP) – UTC(NIST). The standard deviation of the residuals to the smoothing for the complete period is as follows:

raw values:	7.53 ns
corrected values for ephem.:	5.39 ns
corrected values for iono.:	6.46 ns
corrected values for ephem. + iono.:	3.22 ns

Each correction decreases the total standard deviation with a clear improvement where both of the corrections are applied.

The residuals to the smoothing for each data point are presented in Fig. 1 to 4. The comparison of these figures gives the evidence of the improvement of the 'precision of reading UTC(OP) – UTC(NIST)' when correcting one or the other error source. The effect is yet more clear with the use of precise ephemerides together with measured ionospheric delays. In this case, the daily standard deviations of the residuals (see Fig. 5) unquestionably drop. They collapse to values below 4 ns for nearly the entire period under study.

Some comments should be added to this general overview:

During the period under study, SA was on from the beginning till 1990 August 10 (MJD 48113). Fig. 1 shows that it did not affect our computations using strict common views. This is in agreement with Ref 6. Among others, satellite 12 presented very large residuals for some days in August. This effect completely disappears only when corrections for precise ephemerides are applied (Fig. 2). These very poor broadcast ephemerides for satellite 12 are observed during its eclipse season. This phenomena was already observed[4] for satellites equipped with rubidium clocks, which are more sensitive to thermal environment. However, this explanation does not seem to be valid here since the satellite 12 was probably equipped with a cæsium clock at that time.

The examples of satellites 12 and 13, underlined on Fig. 1 to 4, show that the use of precise ephemerides helps to smooth the daily residuals for each common view track while the use of ionospheric measurements tends rather to decrease the biases between satellites. These two effects were already shown individually[4, 11]: here they combine to reduce the uncertainty of the time comparison (Fig. 4).

The favorable effect of applying these two corrections is linked to the particular long baseline (7400 km) between the two sites. This baseline requires that common view observations often have low elevations so that precise knowledge of satellite positions and of ionospheric conditions are needed.

Daily values of UTC(OP) – UTC(NIST), at 0h00 UTC, have been estimated from the smoothed data points. The changes brought by the application of corrections to these values are shown on Fig. 6. The ionospheric measurements, which improve the estimate of the signal delay over the ionospheric model, cause a global shift of about 7 ns. Precise ephemerides correct anomalies due to some satellites with poor broadcast ephemerides. Though we have here no absolute test, the accuracy of the time transfer is probably improved[3].

The Allan deviation of the daily raw and corrected values of UTC(OP) – UTC(NIST) at 0h00 UTC is given on Fig.7 and 8 with a basic sample duration equal to one day. It is impossible to get an estimate of the Allan deviation on a shorter evenly–spaced time interval since the scheduled common views OP–NIST are spread over 14 hours each·day. Raw data is 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.

CONCLUSIONS

A two–month study of time transfers between OP and NIST shows that the consistency of long–distance GPS time comparisons is largely improved by the use of accurate antenna coordinates, precise satellite ephemerides and measured ionospheric delays. The average of the daily biases between satellites drops to 3 ns. At that level of precision, the local time scales are completely accessible for averaging time of the order of one day. This performance competes with that is observed for short–distance time comparisons[1].

Very soon, it may be necessary to refine the conditions of operation: calibration of GPS receivers, unification of receiver software, control of multipath interferences, use of ultra–precise ephemerides, use of Earth tides model...etc.

Another experiment with a third laboratory in Japan in which the three links could be corrected for precise ephemerides and ionospheric measurements is now in progress; it should give an interesting test of the accuracy of GPS time transfer.

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ACRONYMS

BIPM	Bureau International des Poids et Mesures
C/A–Code	Coarse/Acquisition Code
CRL	Communications Research Laboratory
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
NIST	National Institute of Standards and Technology
NSWC	Naval Surface Warfare Center
OP	Observatoire de Paris
P–Code	Precision Code
SLR	Satellite Laser Ranging

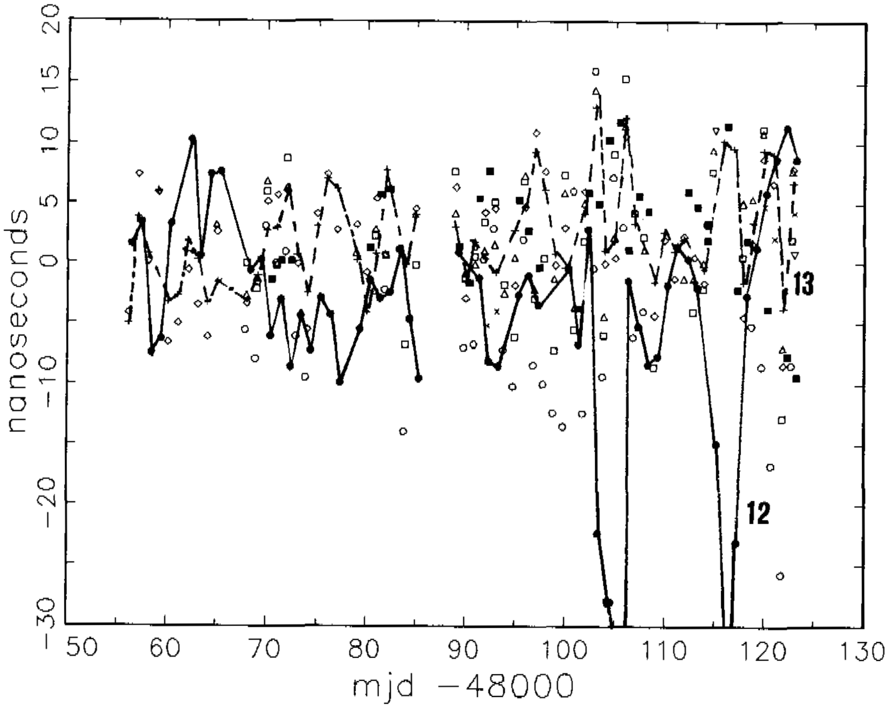

FIGURE 1. GPS time transfer UTC(OP) - UTC(NIST): residuals to the smoothed raw values (two points corresponding to PRN 12 are outside the frame).

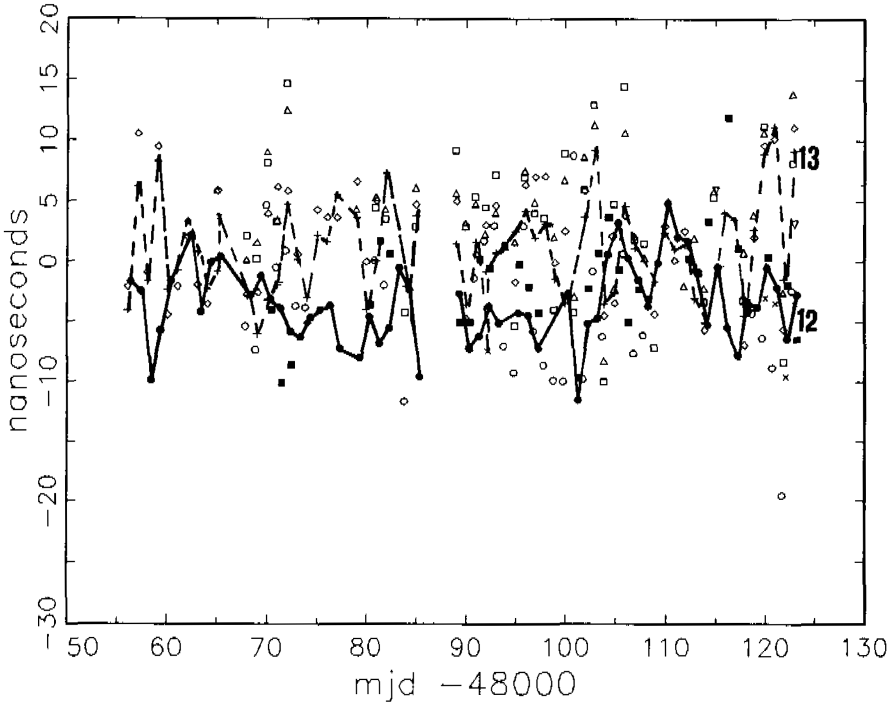

FIGURE 2: GPS time transfer UTC(OP) - UTC(NIST): residuals to the smoothed values previously corrected for precise satellite ephemerides.

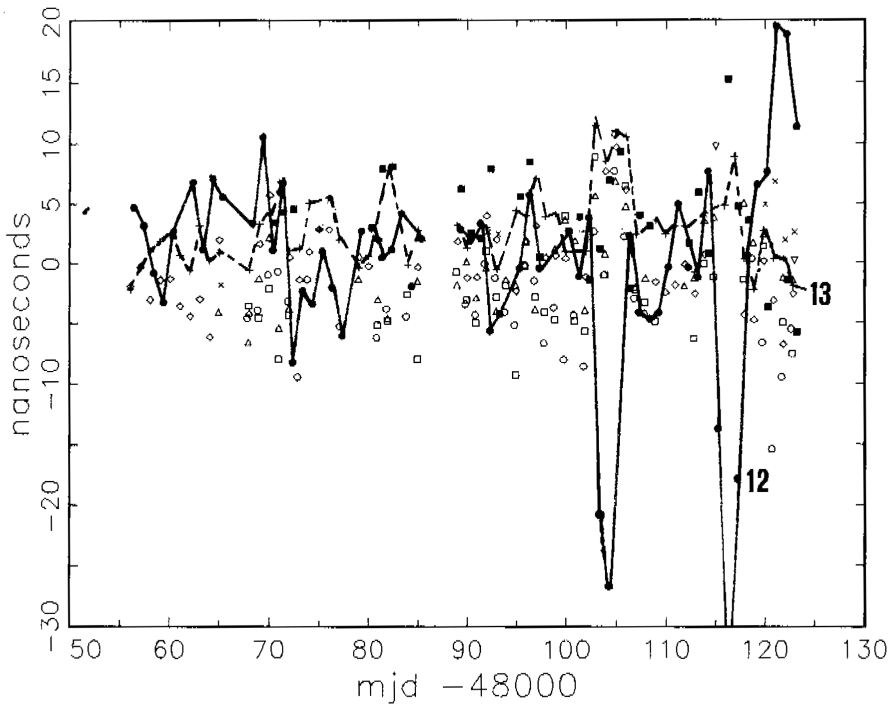

FIGURE 3: GPS time transfer UTC(OP) - UTC(NIST): residuals to the smoothed values previously corrected for measured ionospheric delays.

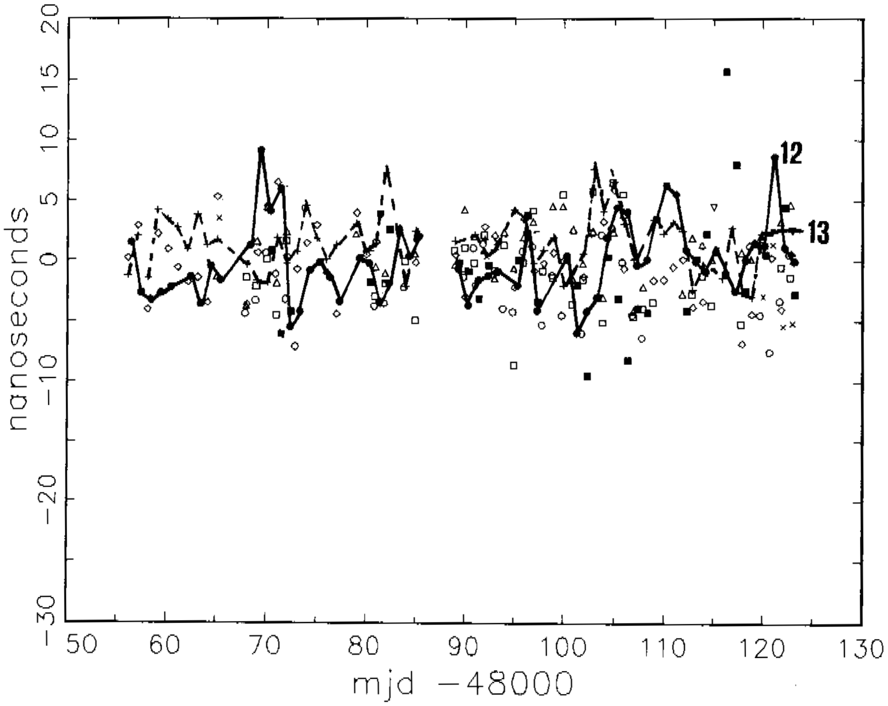

FIGURE 4: GPS time transfer UTC(OP) - UTC(NIST): residuals to the smoothed values previously corrected for precise ephemerides and measured ionospheric delays.

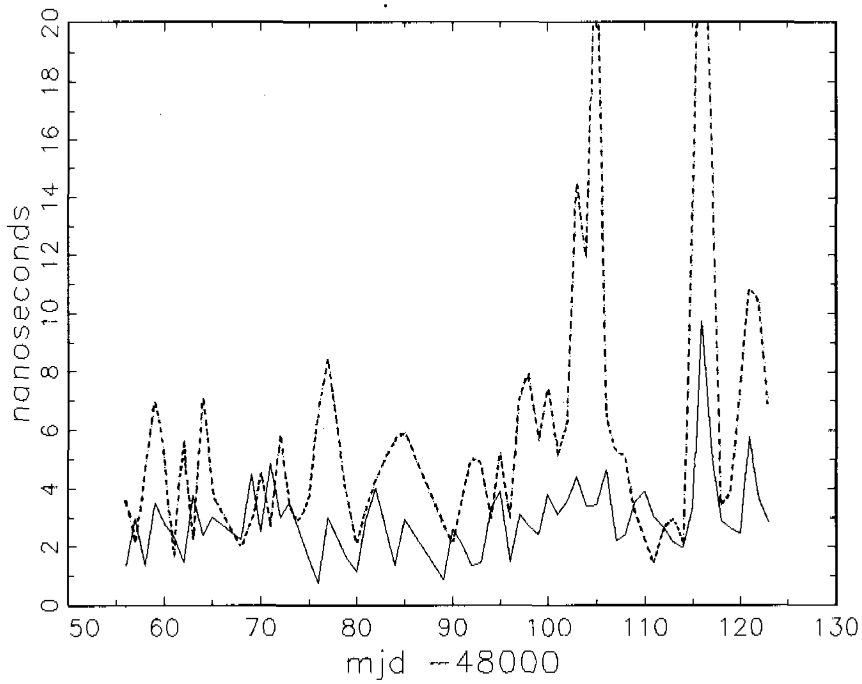

FIGURE 5: GPS time transfer UTC(OP) - UTC(NIST): daily standard deviations of the residuals obtained with:

- - - - - - - - - raw data,

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

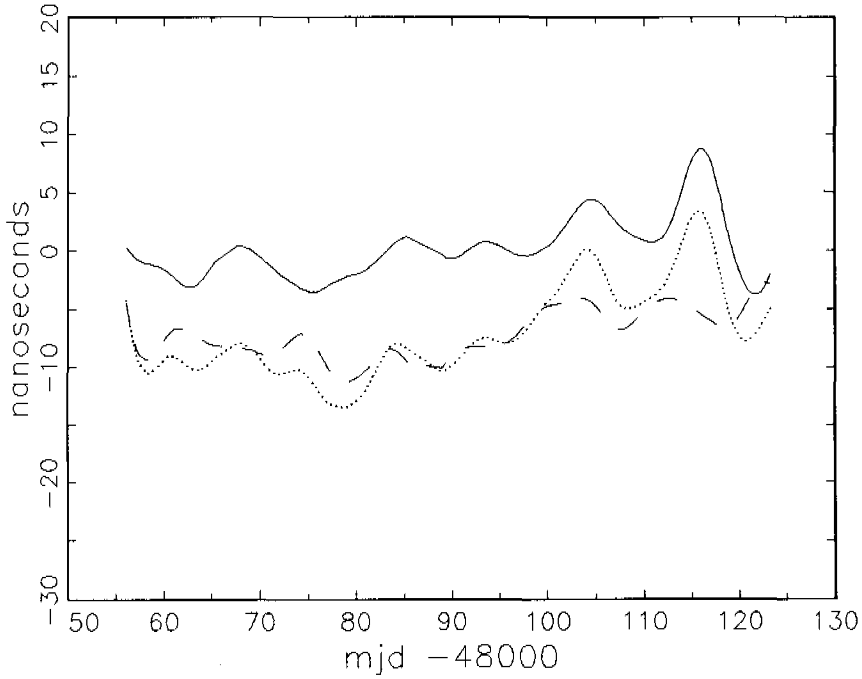

FIGURE 6: Difference between the corrected and the raw values UTC(OP) - UTC(NIST). The corrected values UTC(OP) - UTC(NIST) are obtained with:

———— precise ephemerides,

— — — — measured ionospheric delays,

.... precise ephemerides and measured ionospheric delays.

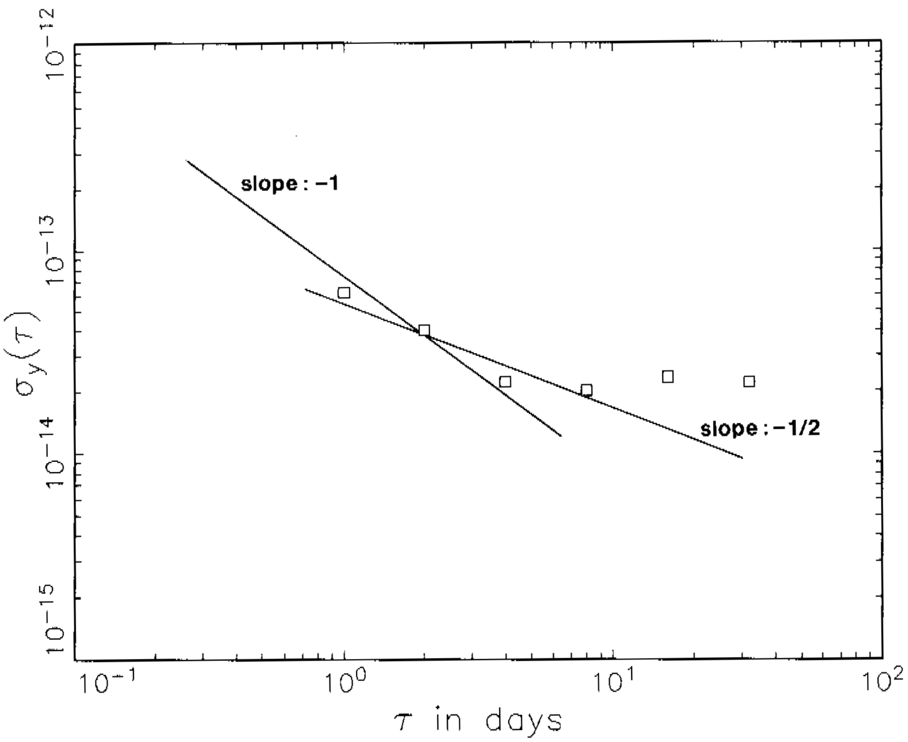

FIGURE 7: Allan deviation of the raw values UTC(OP) - UTC(NIST).

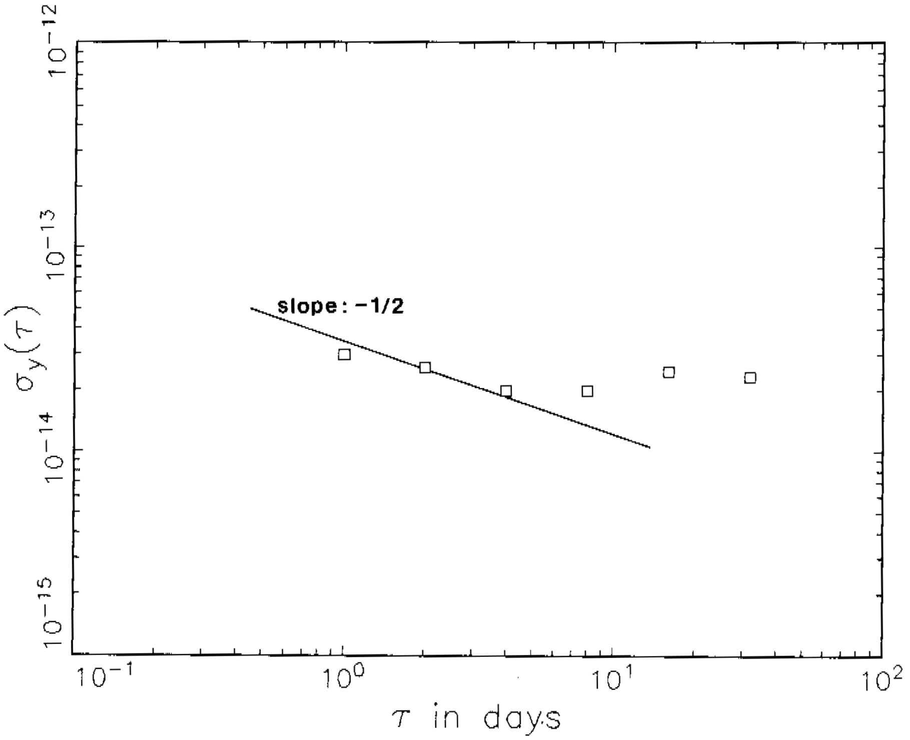

FIGURE 8: Allan deviation of the values UTC(OP) - UTC(NIST) after correction for precise ephemerides and measured ionospheric delays.

QUESTIONS AND ANSWERS

David Allan, NIST: How do you combine the nine readings of each satellite each day?

Dr. Thomas: We did smoothing and then took the value each day at zero hours, UTC.

Mr. Allan: Are all values treated equally?

Dr. Thomas: Yes.

Anthony Liu, The Aerospace Corporation: By what method do you use the differential correction for your ephemeris?

Dr. Thomas: We get the parameters for the precise ephemeris each 15 minutes. It is a little difficult to explain here, but it is in the paper.

Mr. Liu: What is the general magnitude of the correction in meters or other units?

Dr. Lewandowski: It can reach 10 meters. Generally it is not more than 3 to 5 meters.

Unknow Voice: I would add that the uncertainty of the DMA precise ephemerides are about three meters. A study that was made last year showed that the broadcast ephemerides differed by an average of about 5 or 6 meters. For rubidium equipped satellites, this difference can get to 30 meters during eclipses.

Michel Grandveaud, Paris Observatory: I would like to know whether the same filtering was used on the data and the corrected data and whether you observed a bias between the results of these two filterings?

Dr. Thomas: The filtering was the same for both cases. Yes, there was some bias. It is shown in the paper.

Tom McCaskill, Naval Research Laboratories: We are looking at the use of precision clocks in a fairly complex system. What we have seen on the frequency stability profile in what you have presented and in the previous paper and you can identify from the slopes of the frequency stability profile the types of noise on the clocks. The clocks have been very well characterized in terms of the types of behavior. If you use the data to determine the slope, then you can identify the random noise process. If the alopes do not agree with the known behavior of the clock, then the noise is coming from some other part of the system. This sort of behavior tells you that it is a non-clock process, or at least that it is not a well behved clock.