A CALIBRATION OF GPS EQUIPMENT AT TIME AND FREQUENCY STANDARDS LABORATORIES IN THE USA AND EUROPE

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ABSTRACT

The method of clock comparisons using GPS satellites in common view is now widely used in the time laboratories which participate in the international unification of time under the coordination of the Bureau International de Poids et Measures (BIPM). We report here the results of a campaign of calibration of time delay in GPS receivers under the auspices of the BIPM with the assistance of the National Bureau of Standards (NBS), Boulder, CO. This trip in the United States and in Europe was performed from the 29 September 1986 to 27 October 1986. The Institutes and Laboratories visited during the trip were:

National Bureau of Standards, Boulder, USA
Observatoire de Paris, Paris, France
Istituto Elettrotecnico Nazionale, Torino, Italy
Technical University of Graz, Graz, Austria
Institut fur Angewandte Geodasie,
    Wettzel, Fed. Rep. of Germany
Physikalisch Technische Bundesanstalt,
    Braunschweig, Fed. Rep. of Germany
Van Swinden Laboratory, Delft, Netherlands
National Physical Laboratory, Teddington, England
United States Naval Observatory, Washington, USA

INTRODUCTION

The method of clock comparisons using GPS satellites in common view is now widely used in the time laboratories which participate in the international unification of time under the coordination of the Bureau International de Poids et Measures (BIPM). GPS time receivers are in operation in the USA, Canada, several countries in Europe, India, Japan, Australia, and soon in Israel, South Africa, and China. Thus 60 percent of the clocks which enter in the establishment of the International Atomic Time (TAI) are directly linked by GPS, and all of the primary frequency standards contributing to TAI use the GPS common view technique for transferring the length of the second. All the laboratories evaluated follow tracking schedules of simultaneous (common view) observations devised so that a number of errors vanish or are strongly reduced (1). It was thus expected to reduce the uncertainties of the GPS time comparisons to 10 ns. The laboratories which do not yet have a GPS time transfer receiver are usually linked to GPS equipped laboratories by LORAN-C. As the distances are often short, the random uncertainties of these remaining LORAN-C links may be as small as 50 ns on 10 day averages. In the pre-GPS era, the uncertainties of the long distance time comparisons by LORAN-C were on the order of several hundreds of nanoseconds, and large areas of the Earth were not covered. The GPS common view technique has brought a drastic improvement to world-wide time metrology both in precision, accuracy and coverage.

However, the expected accuracy of 10 ns using GPS in the common view method has not been fully realized. The difference between the portable clock trips and GPS in common view is often tens of nanoseconds, even 100 nanoseconds. The reasons for the insufficient GPS accuracy can be divided into three groups:

(a) Inaccuracy of the GPS
(b) Local problems
(c) Data processing differences

Errors in time transfer via a single GPS satellite are due to errors in: satellite ephemerides, ionospheric modelling, tropospheric modelling, local antenna coordinates, calibration of delays in local equipment, or due to multipath interference. Inaccuracy of the GPS refers to errors in the satellite ephemerides and ionospheric models as transmitted from the satellites. The tropospheric model is fixed in the receivers and is typically a simple cosecant function of elevation normalized by a function of local height. Errors here might be considered as either part of the GPS system or a problem with the local receiver and environment. Errors in local antenna coordinates or equipment calibration delays or multipath around the antenna are local problems. Third we note that there are systematic errors in GPS common view data. A time series of common view measurement differences at one sidereal day intervals with a given satellite (as defined by the tracking schedule) can be biased from a similar time series made using a different satellite, or even using the same satellite at a different time (figures 1 and 2). Because of this, different methods of processing common view data can yield significantly different results.

Inaccuracy of the GPS

This inaccuracy can be noticed by studying common view closures around the Earth. These closures should be near zero. However, they give values up to 100 ns (see figure 3). The round-the-world closures using different pivots show similar behavior (figure 4). This leads one to think that the closure error comes from satellite ephemerides and from the ionospheric model but not from the local stations. However one notes that during the last months the closures are getting smaller and do not in general exceed 20 ns. The biases noticed between the results of different satellites which are of the order of a few tens of nanoseconds have probably the same origin as the closure error.

Local Problems

The quality of data is degraded by several local sources of errors:

1) Wrong calibration of GPS receivers (instrumental delay, antenna cable, connection to the local clock)
2) Poor shape of the pulse of the local time reference
3) Tropospheric correction error
4) Multipath due to signal reflection at the receiving site
5) Errors in antenna coordinates

Data Processing

There are different ways to process GPS data. The NBS method uses time series as defined by the tracking schedule, interpolates for missing points or outliers, weights and smooths the individual time series separately, then combines them to form a weighted average (2). The BIH method averages data taken during 10 days from the same time series defined by the tracking schedule without interpolating points, then combines to form a simple average. A third method used by USNO, though with a different focus, is to take as much GPS-minus-Master-Clock data as possible and average for each day. This last is not a common view approach. It does not seem that the results of various common view techniques differ by more than a few nanoseconds for a particular satellite in the tracking schedule. The main source of difficulties are the biases between satellites.

Data errors due to errors in ephemeris, ionospheric models, or tropospheric models could be reduced with post-processing if we had additional data such as precise ephemerides of the satellites or better models and measurements of the refraction. Errors due to the calibration of receiver and laboratory delays and to the adopted station coordinates can be significantly reduced by appropriate measurements. The main goal of this paper is to describe the results of the calibration of delays performed by the Bureau International de Poids et Measures (BIPM) and the National Bureau of Standards (NBS), but we will also consider the antenna coordinates. We note that efforts are underway to standardize data processing methods.

CALIBRATION

Campaigns of calibration of GPS receivers have been executed in the past, particularly that of the Naval Research Laboratory in December 1984 (3) and that of National Bureau of Standards in April 1985. But since then new receivers have been installed and some software improvements have been made. This trip in the United States and in Europe has been performed from the 29 September 1986 to 27 October 1986. The Institutes and Laboratories visited during the trip were:

National Bureau of Standards, Boulder, USA	(NBS)
Observatoire de Paris, Paris, France	(OP)
Istituto Elettrotecnico Nazionale, Torino, Italy	(IEN)
Technical University of Graz, Graz, Austria	(TUG)

Institut fur Angewandte Geodasie, Wettzel, Fed. Rep. of Germany	(IFAG)
Physikalisch Technische Bundesanstalt, Braunschweig, Fed. Rep. of Germany	(PTB)
Van Swinden Laboratory, Delft, Netherlands	(VSL)
National Physical Laboratory, Teddington, England	(NPL)
United States Naval Observatory, Washington, USA	(USNO)

A summary of data pertaining to each laboratory's clock ensemble and GPS equipment is contained in tables 1 - 4.

We will say a few words about the confidence of the mean. If the deviations in the data have a spectrum consistent with white noise, then the standard deviation divided by the square root of the number of measurements gives the confidence in the estimate. A bias factor for a data set can be used as a test for whiteness, as well as to determine the confidence of the mean for non-white data (4). We have used bias factors to determine the confidence in our mean values (Table 5). Much of the data was not white, but showed a noise type similar to other propagation noise such as Loran-C and WWVB (5,6).

The reference for these calibrations was the receiver NBS10 located at the National Bureau of Standards. Another receiver NBS03 which we are going to call "portable" was calibrated with respect to receiver NBS10, for a period of several weeks immediately before being transported to Europe. Unfortunately, there was apparently some error in this calibration which became apparent as follows. A third receiver NBS51 was calibrated against NBS10 during the same period as NBS03 and then shipped to OP for arrival before the trip. This was done to serve as a back-up portable receiver for NBS03 during the calibration campaign in Europe, and then to remain at OP as a replacement for NBS06 which was having some problems. Since both receivers had been calibrated against the same standard within a few weeks, it was expected their difference should have been within a few nanoseconds upon arrival of the "portable" NBS03 at OP. Instead the initial value on Oct 1 at OP was:

NBS03 - NBS51 = 9.2 ns, rms = 3.4 ns, conf. mean = 0.7 ns.

A similar value was found at the end of the campaign in Europe, from Oct 18-21 we have:

NBS03 - NBS51 = 10.9 ns, rms = 4.1 ns, conf. mean= 1.0 ns.

This value was again confirmed upon return to Boulder. We find for the eight days Oct 29-30, Nov 1-4 and combined with Nov 10-11:

NBS03 - NBS10 = 9.5 ns, rms = 2.4 ns, conf. mean = 0.3 ns.

We have studied data from before the trip, as well as carefully checked the hardware in the receiver upon return. The noise bandpass of the antenna package looked quite similar to its appearance before the trip. There were no abnormalities found in the receiver such as voltage offsets in the op-amps that could cause a time bias. The data from before the trip indicate that the value used initially was correct, assuming the receiver software had initially been set with a delay of 50 ns, as is our usual custom. In that we have no records what this initial value actually was, this value of 50 ns is suspect.

In any case, the measurements from the trip have all been adjusted for a value of 9.9 ns, by subtracting this value from all NBS03-site measurements. These results, summarizing the values from the calibration, are in table 5. Thus we are referencing the "portable" receiver NBS03 against NBS10 at the NBS for this calibration, using NBS51 as a transfer standard initially and finally in Europe with verification directly against NBS10 at the end.

Several repeated measurements in table 5 give indications of the reproducibility of the calibrations. Measurements made at OP at the beginning and end of the travel in Europe, NBS03 - NBS06, are 7.5 ns with a confidence of 1.8 ns, at the beginning, and 8.9 ns with a confidence of 0.6 ns at the end. The trip involved a period of some 17 days of travel, carrying equipment in a car, packing and unpacking, with all the associated vibrations and temperature changes. Simultaneous with the NBS03 - NBS06 measurements were measurements against the transfer standard, NBS03 - NBS51: -0.7 ns with a confidence of 0.7 ns, at the beginning of the travel in Europe, and 1.0 ns with a confidence of 1.0 ns at the end. We compare these also to the -0.4 ns measurement with a confidence of 0.3 ns made of NBS03 - NBS10 directly at the very end of the trip in Boulder. This was after airplane travel and rough handling. Indeed during the trip to Boulder the batteries which provide power for the non-volatile memory were knocked loose. This memory holds data such as the almanacs of the satellites needed for lock. From this experience we conclude that reproducibility is of the order of 1 - 2 ns.

It should be noted that the absolute delays of NBS10 and its antenna cable have not been measured directly. Rather receiver NBS10 has been estimated to have a delay of 53.0 ns, and the antenna cable pulse delay has been measured with a digital counter. This latter measurement is known to exceed the group delay measurement by about 1% of the total delay for RG-58 cable. We have found this experimentally by inserting a cable in series with an existing antenna cable and noting the change in receiver bias. This has also been discussed by DeJong (7). The cable accompanying NBS03 was measured by the pulse method, and this value has been compared to a group delay measurement using the Mitrex modem at 70 MHz made during the visits to TUG and VSL, and again upon return to NBS. The results, which also verify this 1% difference are in Table 6.

The portable equipment consisted of the microprocessor-receiver, its antenna and preamplifier-mixer, a calibrated antenna cable, and a printer for recording data. The individual labs supplied a second cable to the antenna providing power and 50 MHz for the mixer, 5 MHz and a calibrated 1 pps connection to the local reference, UTC(lab). As mentioned above, the delays have been adjusted so that, for simultaneous tracking of the same satellite:

$$(\text{NBS03 measurement}) - (\text{NBS10 measurement}) < 1 \text{ ns}$$

The portable receiver in each laboratory was connected to the same clock as the local receiver, and the antenna of the portable receiver was placed close (less than 10 meters, except at NBS) to the local antenna (table 4). At the beginning of the trip we made measurements at each location for 48 hours. This experiment allowed us to see that a period of 24 hours is sufficient to perform a good calibration. At the end of the travel, we made measurements for 24 hours only. The results of the calibration are in table 5.

In view of the large value of "portable receiver - local receiver" at IFAG, the delay of the local receiver was corrected immediately.

COORDINATES OF THE ANTENNAS

Checking antenna coordinates was a second purpose of this trip. Let us assume that the coordinates of the antennas are exactly known in a global geodetic reference system R, but that there is an error E in the position of the observed satellite with respect to R. Since we are using the common view technique it is only the effect of E on the differences of ranges to the satellite from the participating stations that contribute to the synchronization error. Further, the tracking schedule has been designed to minimize this synchronization error. But, if the station coordinates have errors in the reference system R, these errors have a direct impact on the synchronizations proportional to the projection of this error vector on the direction vector to the satellite.

Therefore, the antenna coordinates must fulfill the following requirements:

(a) They must be accurately determined in a common homogeneous geodetic reference system. Preferably the uncertainties should be of the order of one meter or less.

(b) In order to reduce the residual errors of the common view method, the satellites and antenna coordinates should be expressed in the same geodetic reference system. But this requirement is less strong than (a): errors of 10 to 20 meters with respect to the station network are acceptable.

The transmitted ephemerides of GPS satellites are currently expressed in a coordinate system which is an approximation of the World Geodetic System 72 (WGS72) with an accuracy of 10 to 15 meters. This is in the process of being changed to WGS84. In order to determine the station coordinates in the system (requirement (b)), one could make use of the navigation solution of the GPS receiver. But this is not a satisfactory method because the accuracy is only of the order of 10 meters. However, if this solution was performed in locations A and B simultaneously using the same satellites, the difference in coordinates between these stations could be obtained to the order of a meter (8). Thus if coordinates were known well at A this "common view positioning" could be used to establish them at B. Perhaps a better method would be to obtain the antenna coordinates by Doppler positioning with geodetic receivers of the TRANSIT system, with an accuracy of about 1 meter. TRANSIT is a U. S. Department of Defense positioning and navigation system currently operated by the Navy. These coordinates are expressed in the Naval Surface Weapons Center (NSWC) system and must be transformed into the WGS72. In practice, most of the visited laboratories have obtained the coordinates of their antennas from the European Campaign of Doppler Point Positioning in 1979 (9), but some have not (see Table 4), and it might be advisable to extend the Doppler positioning to them. When the coordinate system of the GPS satellites change, one must globally adjust the system of antenna coordinates, but in the meantime they should be kept fixed, except for improvements in the common agreed reference system.

CONCLUSIONS

The results of the GPS calibration trip bring a significant improvement in the time comparisons. Over long distances, calibration of GPS time transfer equipment is easier to perform and more accurate than the calibration of differential delays by clock transportation. These calibrations should be extended to all laboratories which participate in the world wide unification of time. They should also be repeated from time to time in order to check the aging of the receivers. Although the BIPM intends to perform future calibrations of GPS time receivers by use of a portable receiver, it would be clearly impossible for BIPM to visit all the laboratories on a regular basis. A possible organization could be that the national laboratories make regional calibrations (for instance within Europe or Japan), so that the BIPM portable trip be restricted to one laboratory of each region. The BIPM is ready to coordinate these calibrations. It should be noted that it is possible for a single person to make a calibration trip with the help of the visited laboratory. This opens the possibility of inexpensive trips, perhaps by combining calibrations with attendance at meetings.

Our calibration trip has also given the opportunity to stress the importance of accurate antenna coordinates and of the quality of the local equipment generating the UTC(lab) pulses, as well as to discuss the problem of biases between measurements via different satellites.

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We wish to express our gratitude to our colleagues from visited laboratories for their friendly welcome and full collaboration without which this work could not have been accomplished. We also wish to thank Dr. J. Barnes and Mr. D. Allan for their help in reading this paper.

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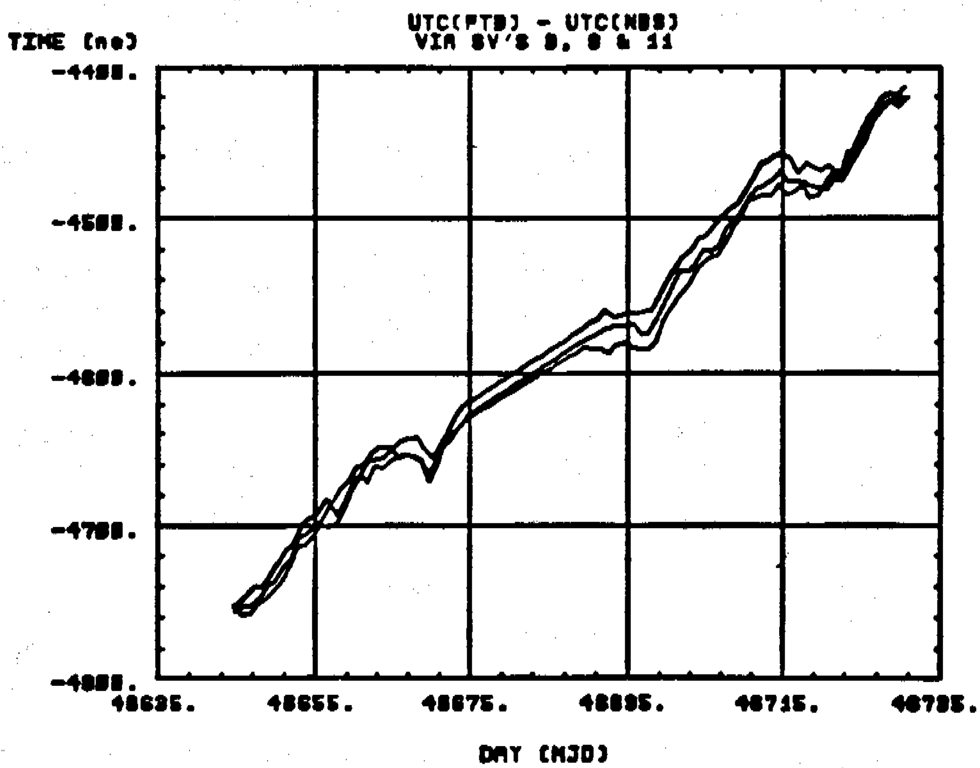

Figure 1: Biases between different SV's used in common view between PTB in Europe and NBS in Western North America

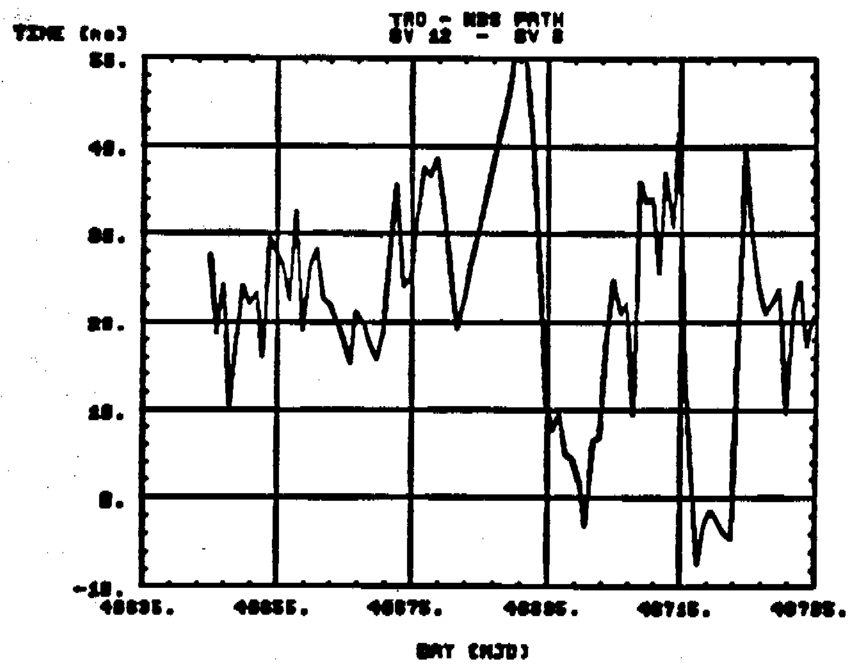

Figure 2: Differences of TAO - NBS Japan to Western North America common view data via SV 12 minus SV 6 showing the bias between them. The mean bias is 22.4ns.

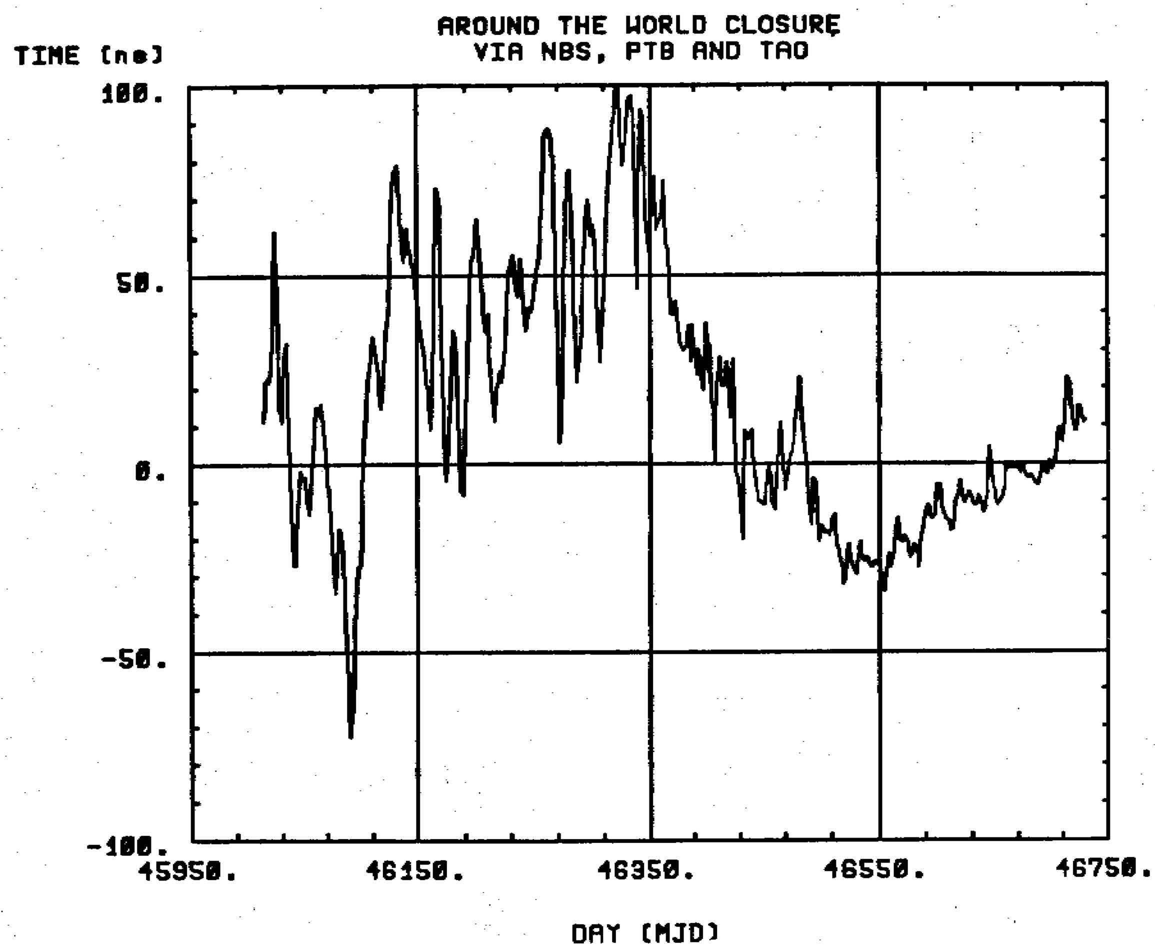

Figure 3: Residuals after transferring time via GPS satellites in common view around the world for about two years using NBS in Boulder, Colorado, USA, PTB in Braunschweig, W. Germany, and TAO in Tokyo, Japan as pivots. MJD 46066 is January 1, 1985, and MJD 46431 is January 1, 1986.

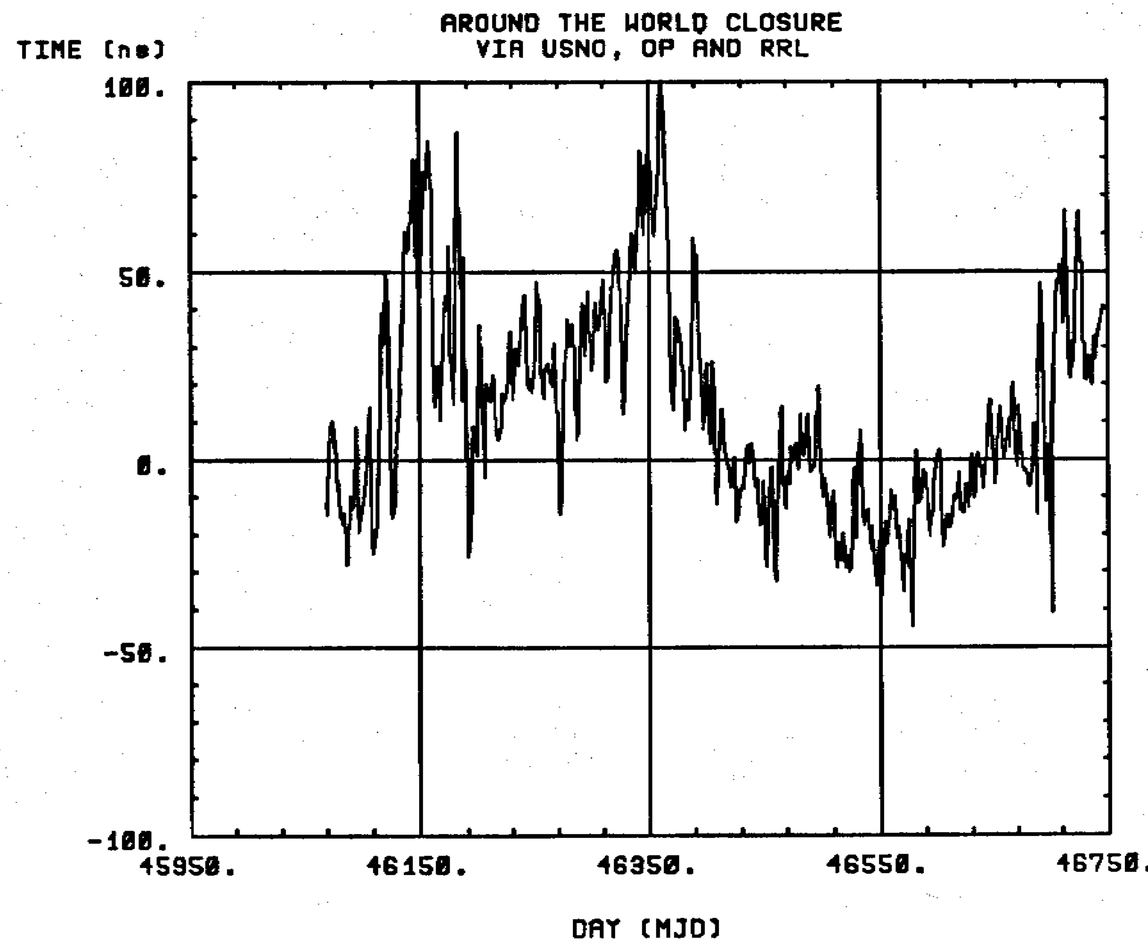

Figure 4: Residuals after transferring time via GPS satellites in common view around the world for about two years using USNO in Washington D.C., USA, OP in Paris, France, and RRL in Tokyo, Japan as pivots. MJD 46066 is January 1, 1985, and MJD 46431 is January 1, 1986.

TABLE 1 : Clock ensemble (* stands for yes)

LAB. (i)	Clock ensemble	Source of UTC(i)	Point of UTC(i)	temp. control	humid. control	Faraday shield
NBS	16 Ind.Cs 2 lab.Cs 2 passive H Masers	13 Cs 1 lab.Cs 2 H Masers	microstepper output plus software correction	*		*
OP	5 Ind.Cs	1 Cs	master clock front	*		
IEN	5 Ind.Cs	1 Cs + microstepper	start of time interval counter	*		
TUG	2 Ind.Cs	1 Cs +	master clock front	*	*	
IFAG	3 Ind.Cs 2 active H Masers	1 Cs + microstepper	start of time interval counter	*		*
PTB	10 Ind.Cs 2 lab.Cs	1 Ind.Cs + microstepper steered by PTB primary standard	start of time interval counter	*		*
VSL	4 Ind.Cs	1 Cs	start of time interval counter	*	*	*
NPL	7 Ind.Cs 1 lab.Cs	1 Cs 1 Cs	start of time interval counter	*		
USNO	60 Ind.Cs 2 active H Masers	1 H Maser steered by nominally 25 Cs selected clocks (selection on the basis of observed 5 day stability)	master clock at measurement system	*		

Table 2. Shape of the 1pps of the local time reference. The trigger point for the counter in the receivers was 0.5 v.

LAB	90% Rise Time (ns)	Peak Voltage Levels
NBS	4	
OP	4	0 - 2.25
IEN	20	0 - 2.1
TUG	6	0 - 5
IFAG	<40 (unable to measure)	0 - 10
PTB	14	0 - 2.5
VSL	10	0 - 2.0
NPL	20	1 - 4.5
USNO	5	0 - 4.0

TABLE 3. Some information on receivers and antennas
(* stands for yes)

LAB. (i)	RCV design	Revised iono. corr. (1985)	Original iono. corr. with 2pi error	Antenna non-reflecting plane	port. ant. NBS calibrated cable	port. ant. locally calibrated cable
NBS	NBS	*		*	*	
OP	NBS	*			*	
IEN	NBS	*			*	
TUG	STI		*		*	
IFAG	NBS	*			*	
PTB	NBS	*				*
VSL	NBS	*				*
NPL	NBS	*			*	
USNO	STI	*		*	*	

Identification of a commercial company does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that any identified entity is the only or the best available for the purpose.

TABLE 4. Coordinates of antennas (* stands for yes)

LAB.	Doppler solution	GPS navigation solution	distance between local antenna & portable antenna
NBS	*		78.2m
OP	*		0.2m, 5m
IEN	*		3.2m
TUG	*		1.2m
IFAG	*		app 10m
PTB		*	0.8m
VSL	*		0.2m
NPL		*	1.0m
USNO	*		app 2m

TABLE 5. Calibration offset: NBS03 - site
Calibrated Against NBS10

LAB (i)	Date	No pts	Mean offset (ns)	RMS (ns)		confidence of mean (ns)
NBS	Sep 8-11	70	**	2.7		0.3
OP	Oct 1	23	7.5	4.6	(NBS06)	1.8
		23	-0.7	3.4	(NBS51)	0.7
IEN	Oct 3-4	42	-18.1	2.2		0.5
TUG	Oct 6-7	26	3.3	3.6		0.7
IFAG	Oct 8-9	35	85.4	7.3		3.6
PTB	Oct 11	20	9.3	2.2		1.3
VSL	Oct 13	18	-16.8	2.9		0.7
NPL	Oct 15,16	23	24.1	2.6		0.5
OP	Oct 18-21	102	8.9	3.4	(NBS06)	0.6
		101	1.0	4.1	(NBS51)	1.0
USNO	Oct 23-24	23	25.3	3.6		1.3
NBS	Oct 27-28 & Nov 6-7	78	-0.4	2.4		0.3

Table 6. Calibrations of NBS03 antenna cable via Mitrex modem

Location	Calibration Value
TUG	229.1
VSL	229.4
NBS	229.6

QUESTIONS AND ANSWERS

LAUREN RUEGER, JOHNS HOPKINS: Did you measure the temperature of your cables? This is a long enough time that a delay change of a half nanosecond can be caused by clouds coming over on a sunny day with 100 feet of cable exposed on a roof. We have shielded the cables from this effect. Have you paid attention to that problem?

MR. WEISS: No, we did not use any temperature measurements.

MR. RUEGER: That might reflect in some of the calibration closures that you are seeing.

MR. WEISS: Yes, we had a 45 meter cable, so 100 feet could easily have been exposed. That may be a half nanosecond here and there.

DAVID ALLAN, NATIONAL BUREAU OF STANDARDS: I notice that the USNO STI receiver calibration of 25 nanoseconds. That was previously calibrated with an absolute by Jim Buisson on his earlier trip. Any comment on that?

MR. WEISS: I am not yet informed as to whether that absolute delay value was incorporated in the receiver. I guess that it is not. I wanted to mention, however, that all of the values that I put up for the calibration are all relative to our receiver at NBS, which has not had an absolute calibration yet. They are all relative to our best guess as to what the absolute delay is. If we are going to use new values for calibration, my belief is that we should get some absolute calibrations done. We are making plans to do this during the early pert of next year, January or February.

MR. BUISSON: I have a comment. At NRL, on another project, we have several STI receivers that have been deployed for a year and a half. Recently one has been returned. We did a calibration before it went out and another calibration after it was returned. After eighteen months it had only changed by three nanoseconds. There shouldn't be a reason for a big change in calibration, at least for these STI receivers.

MR. WEISS: Unless someone changes something.

MR. BUISSON: Given the same conditions, yes.

K. UGLOW, ELECTRONICS RESEARCH: The first chart showed the closure going around the world via GPS. I think that you mentioned the ephemeris and ionosphere as being the most likely error sources. What is the outlook for doing that two-way around the world, are there satellites to do that with?

MR. WEISS: I don't think that we can go all the way around the world with two-way yet.

D. SCHAFFER, INTERFEROMETRICS: There are Ku-Band satellites that I am sure are mutually visible all the way around the world. You would have to work out the details with whoever owns them to use them.

MR. WEISS: From North America to Europe we see biases. Depending on which satellite you look at, you get a different answer with GPS. We would like to know what the right answer is but we have no way of knowing what is truth in this situation. We are hoping to use the two-way to study the biasses real carefully.

MR. BUISSON: On that two year chart that showed a cycle of a hundred nanoseconds, that was common view wasn't it?

MR. WEISS: Yes.

MR. BUISSON: That is not ephemeris? To first order ephemeris should cancel out. This would have to be second order. I am sure that the Master Control Center, JPO, would not want that to be called ephemeris. It must be something else.

MR. WEISS: It would have to be differential ephemeris, differential ionosphere or differential troposphere. The only other thing that it could be is local effects, coordinates or multipath.

UNIDENTIFIED QUESTIONER ASKS ABOUT COORDINATE ERROR

MR. WEISS: It couldn't be coordinates because they would have to be changing identically at some set of locations.

GERNOT WINKLER, UNITED STATES NAVAL OBSERVATORY: It could very well be coordinate contribution. You have to remember that the constellation is changing. You have the four minute a day change so that coordinate error that you think stays constant, doesn't stay constant in its contribution to the time scale. It could then very well be coordinate error. I expect to see some effect when we make that coordinate change. You will see the biasses change, no question! Even if everybody makes his correction.

MR. WEISS: Do you think that it is possible to have coordinate errors identical so that the chart looks identical like this?

MR. WINKLER: Well, the stations which you have selected are not that far apart. The aspect is still very similar for these stations.