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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 des Poids et Mesures (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 September 29, 1986 to October 27, 1986.

Introduction

The method of clock comparisons using Global Positioning System (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 des Poids et Mesures (BIPM). GPS time receivers are in operation in the USA, Canada, several countries in Europe, India, Japan and Australia, and soon in Israel, South Africa and China. Thus 75 percent of the clocks which enter into the establishment of the International Atomic Time (TAI) are directly linked between themselves 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 comparison by LORAN-C were of some hundreds of nanoseconds, and large areas of the Earth were not covered. The GPS has brought a drastic improvement to the world-wide time metrology in precision, accuracy and coverage.

However, the expected accuracy of 10 ns using GPS in the common-view method is not fully realized. The difference between the portable clock trips and GPS in common view is often some 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, or calibration of delays in local equipment; or are due to multi-path. 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 we might consider as being either part of the GPS system or a problem of the local receiver and environment. Errors in local antenna coordinates or equipment calibration delays or multipath around the antenna are local problems. Thirdly we note that there are systematic errors in GPS common-view data. A time series of common-view measurement differences at intervals of one sidereal day 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

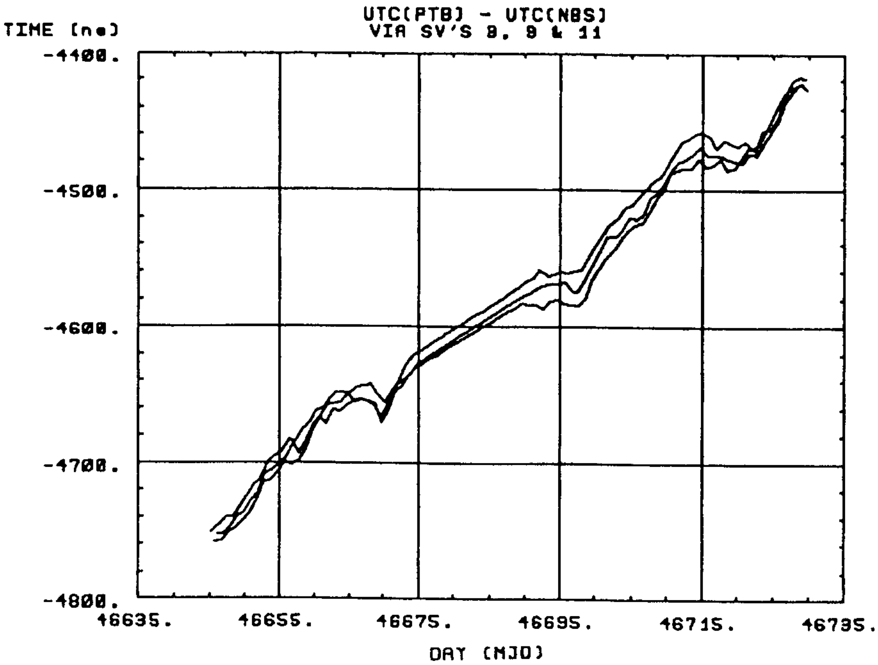

Fig. 1. Biases between different SVs used in common view between PTB in Europe and NBS in Western North America

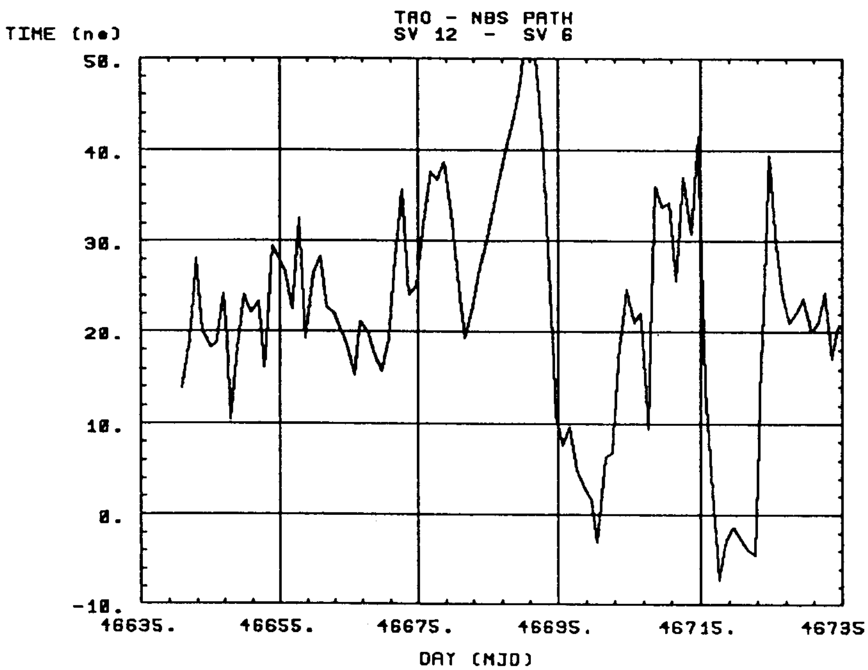

Fig. 2. Differences of TAO–NBS Japan to Western North America common-view data via SV 12 minus SV 6 showing the bias between them. The mean bias is 22.4 ns

same satellite at a different time (Figs. 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 Fig. 3). The round-the-world closures using different pivots show similar behavior (Fig. 4). That leads one to think that the closing error comes from satellite ephemerides and from the ionospheric model but not from stations. However, one notes that during the last months the closures are getting smaller and in general do not 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.

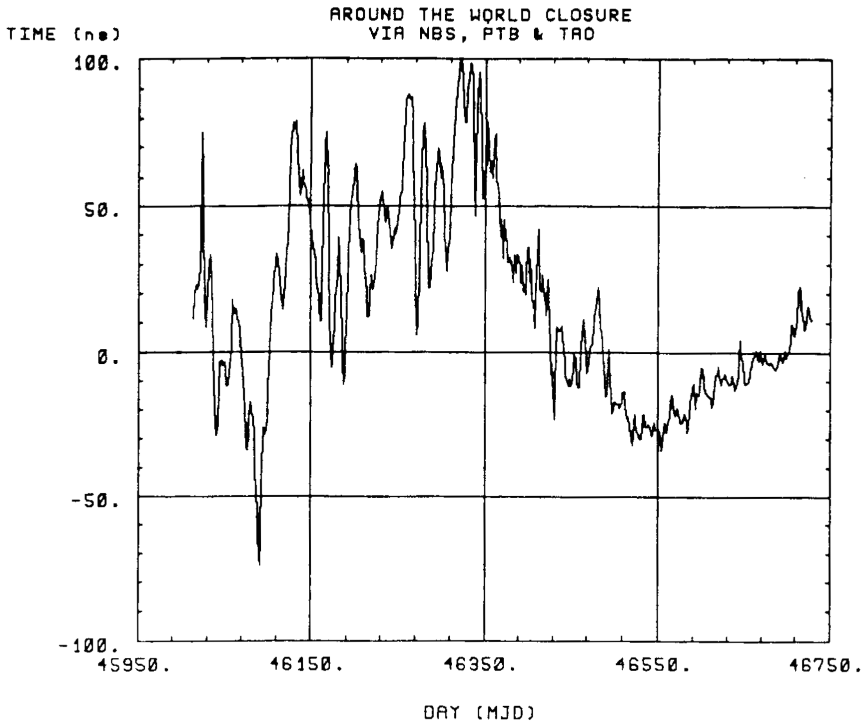

Fig. 3. Residuals after transferring time via GPS satellites in common view around the world for about two years using NBS in Boulder, Colorado, USA, PTB in Braunschweig, W. Germany, and TAO in Tokyo, Japan as pivots. MJD 46066 is January 1, 1985, and MJD 46431 is January 1, 1986

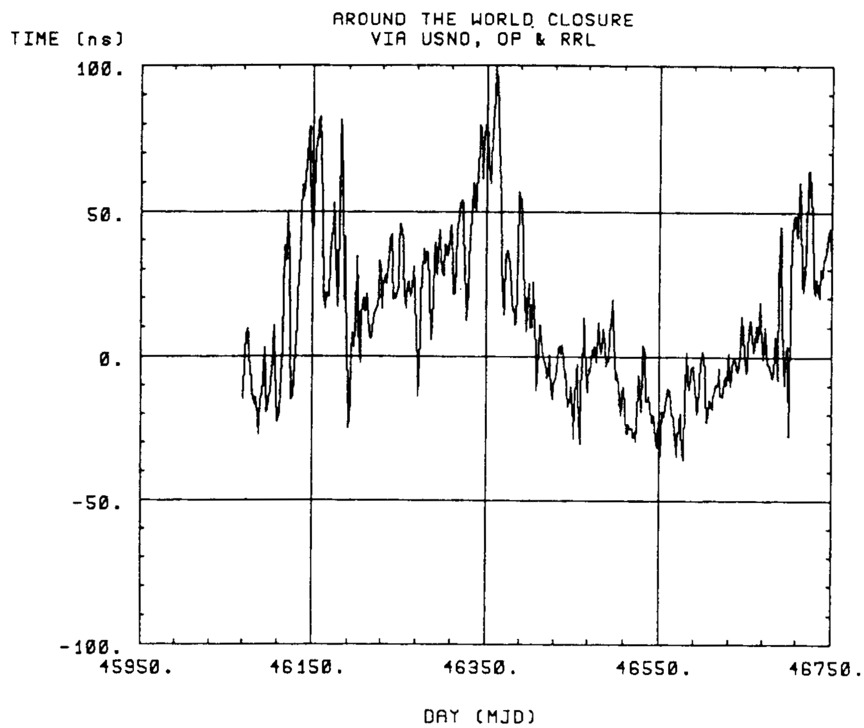

Fig. 4. Residuals after transferring time via GPS satellites in common view around the world for about two years using USNO in Washington D.C., USA, OP in Paris, France, and RRL in Tokyo, Japan as pivots. MJD 46066 is January 1, 1985, and MJD 46431 is January 1, 1986

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. Multi-path 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 BIPM 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 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 ephemerides, ionospheric models, or tropospheric models could be reduced with post-processing if we have 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 des Poids et Mesures (BIPM) and the U.S. National Bureau of Standards (NBS), but we will also consider the antenna coordinates. We note that efforts are under way to standardize data-processing methods.

Calibration

Campaigns of calibration of GPS receivers have been executed in the past. Particularly that of the U.S. Naval Research Laboratory in December 1984 [3] and that of NBS 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 September 29, 1986 to October 27, 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 für Angewandte Geodäsie, Wettzel, Federal Republic of Germany (IFAG)
Physikalisch Technische Bundesanstalt, Braunschweig, Federal Republic of Germany (PTB)
Van Swinden Laboratory, Delft, Netherlands (VSL)
National Physical Laboratory, Teddington, England (NPL)
United States Naval Observatory, Washington D.C., USA (USNO)

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 1). 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. A third receiver NBS51 was calibrated against NBS10 during the same period as NBS03,

Table 1. Calibration offset: NBS03-site. Calibrated against NBS10

LAB	Date	Number of individual measurements[a]	Mean offset[b] (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

[a] An individual measurement is based on 13 minutes' tracking
[b] "Mean offset" = (REF-GPS) as obtained by the portable receiver NBS03 minus (REF-GPS) as obtained by the receiver at the site

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. 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. The results, summarizing the values from the calibration, are in Table 1.

Several repeated measurements in Table 1 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. In between was 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 value with a confidence of 0.3 ns made at the very end of the trip in Boulder, NBS03 − NBS10 directly, after airplane travel and rough handling. Indeed, during the trip to Boulder the batteries were knocked loose which provide power for the non-volatile memory, holding data such as the almanacs of the satellites needed for lock. From these data 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 form 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% approximation, are in Table 2.

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 laboratories supplied: to the antenna, power and 50 MHz for the mixer; and to the receiver a) 5 MHz, b) via a cable of known delay, 1 s pulses from the local reference, UTC (lab). 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 away, except at NBS) to the local antenna. 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.

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

Table 2. Calibrations of NBS03 antenna cable via Mitrex modem

Location	Calibration value (ns)
TUG	229.1
VSL	229.4
NBS	229.6

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 fulfil 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 m 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 m. 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 m. 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 m. These coordinates are expressed in the 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 and it might be advisable to extend the Doppler positioning to them. When the coordinate system of the GPS satellites changes, one must adjust globally 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, it 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, with the help of visited laboratories, it is possible for a single person to make a calibration trip. 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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