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BUREAU INTERNATIONAL DES POIDS ET MESURES

DETERMINATION OF THE DIFFERENTIAL TIME CORRECTION BETWEEN GPS TIME EQUIPMENT LOCATED AT THE OBSERVATOIRE DE PARIS, PARIS, FRANCE, AND THE UNITED STATES NAVAL OBSERVATORY, WASHINGTON D.C., USA

by

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Abstract

The method of clock comparisons using GPS satellites can now reach an accuracy of several nanoseconds. Poor calibration of GPS time receiving equipment is one of the limiting factors to this accuracy. One method which permits removal of calibration errors is the comparison of remote GPS equipment by transporting a portable receiver from one location to another. We report here the results of a comparison of the GPS equipment located at the Paris Observatory (OP) and at the United States Naval Observatory (USNO). This comparison was effected by means of a portable AOA-TTR6 GPS time receiver.

Resumé

La méthode de comparaison des horloges en utilisant les satellites du GPS peut, à ce jour, atteindre une exactitude de quelques nanosecondes. Un mauvais étalonnage des equipments du temps du GPS constitue l'un des facteurs limitant cette exactitude. Une méthode qui permet d'éliminer les erreurs d'étalonnage consiste à comparer des equipments GPS distants par transport d'un récepteur GPS portable. Nous rapportons ici les résultats d'un tel étalonnage des equipments GPS situés à l'Observatoire de Paris (OP) et à United States Naval Observatory (USNO). Cet étalonnage a été effectué à l'aide d'un récepteur de temps GPS portable AOA-TTR6.

INTRODUCTION

The present comparison of GPS time receiving equipment concerns two leading time laboratories, the United States Naval Observatory (USNO) and the Paris Observatory (OP). Both play a major role in international efforts to bring about the unification of time.

The USNO monitors *GPS time* to provide a reliable and stable coordinated reference time scale for the system [1, 2]. As the GPS navigation message includes data giving access to UTC(USNO), and because UTC(USNO) closely follows UTC, GPS is an outstanding tool for the dissemination of UTC. The USNO, with its large number of high quality clocks, is also a major contributor to International Atomic Time. The OP is pivotal laboratory for international GPS common-view time links, and is also a major contributor to International Atomic Time [3].

The method of time transfer between remote locations using GPS satellites in common view has now achieved an accuracy of several nanoseconds [4]. Calibration errors in GPS time equipment (for example, receiver and antenna delays, cable delays, 1 pps distribution) limit this accuracy. One method which permits the removal of calibration errors is the comparison of remote GPS time equipments using a portable GPS time receiving equipment. Such calibrations were initiated in 1984 by the Naval Research Laboratory (NRL) with the support of the USNO [5]. Since then a number of comparisons of remote GPS time receivers have taken place. The USNO and the OP often serve as reference stations.

The GPS time equipment located at the OP and the USNO has been compared directly, in the past, on two occasions: in December 1984 [5] and in October 1986 [6]. A calibration of the USNO and the NBS time receivers using the NRL GPS Time Transfer Receiver Calibrator was performed in 1987 [7]. In 1991 the USNO receiver was again absolutely calibrated by the NRL, but the accurate delay was not introduced into the receiver [8]. The results of the present comparison differ from those of 1984 and 1986. It must be noted however that 1984 comparison had a large uncertainty. This comparison agrees with the 1991 NRL absolute calibration, if we admit that the internal delay of the OP receiver is accurately calibrated.

The OP receiver has been compared 8 times in the last 11 years with the NIST "on line" GPS time receiver. The differences between two receivers have always been within a few nanoseconds, except for the 1985 calibration [5], which had a large uncertainty. The internal delay of the NIST receiver has been verified by an absolute calibration.

The reproducibility of the comparisons from such exercises is a few nanoseconds, but our experience with the long-term stability of GPS time receiving equipment is still limited; drifts or steps of several tens of nanoseconds can occur without being noticed. Some types of GPS time receiver have been shown to be sensitive to external temperature [9,10]. For these reasons, frequent comparisons of GPS equipment are required.

This exercise is associated with a *field trial*, an international two-way time transfer experiment through the satellite INTELSAT (VA-F13) located at 307° E, involving both European and North-American time laboratories [11].

The present comparison was realized following the procedure described in BIPM report 91/6 [12].

EQUIPMENT

The USNO has several GPS time receivers in constant operation in Washington DC. The primary units are an STel 502 single-frequency receiver and a DFR dual-frequency receiver [2]. Both are produced by Stanford Telecommunication Inc. (STel). The STel 502 receiver has been in continuous operation since 1984 and is the source of all GPS data that appear in USNO publications, in the USNO Automated Data Service and supplied to the Bureau International des Poids et Mesures as a contribution to the generation of International Atomic Time. The DFR receiver operates in the authorized mode. Data from this receiver is supplied to the U.S. Air Force and is not normally available to unauthorized users. This dual-frequency equipment is accurately calibrated.

Several receivers are also in permanent operation at the OP [3]. The primary unit since July 1983 has been the single-frequency Allen Osborne Associates (AOA) TTR5 receiver. The OP receiver serves as reference for many international comparisons of GPS time equipment [13,14,15,16].

The present comparison involves the USNO STel 502, the OP TTR5 051 and the portable TTR6 289 receiver belonging to the BIPM and designated BIPM5. The three receivers are single-channel, C/A code receivers. Their principal characteristics are:

Portable receiver: BIPM5	Maker: Allen Osborne Associates, Type: TTR6, Ser. No: 289, Adopted receiver internal delay + antenna cable delay: 292 ns,
OP:	Maker: Allen Osborne Associates, Type: TTR5, Receiver Ser. No: 051, Antenna cable length 33,00 m, Adopted receiver internal delay: 54 ns.
USNO:	Maker: Stanford Telecommunications Inc., Type: STel 502, Receiver Ser. No: 011, Antenna cable length 30,48 m, Adopted receiver internal delay: 135 ns.

The AOA, TTR5 and TTR6 receivers downconvert the L1 frequency (1575,42 MHz) at the antenna level to 75 MHz but the STel 502 does not.

Comparisons at short distances allow cancellation of a number of errors. If the software of the receivers compared is identical, no error should arise from satellite broadcast ephemerides, antenna coordinates or imperfect modelling of the ionosphere and troposphere.

Unfortunately, differences have been found in the software receivers of different type [4,17,18]. The *Group on GPS Time Transfer Standards*, operating under the auspices of the permanent CCDS Working Group on improvements to TAI, chaired by Dr G.M.R. Winkler, has recently issued standards to be adopted by receiver designers and users concerned with the use of GPS time receivers for common-view time transfer [19,20,21]. These standards will soon be implemented on most GPS time receivers.

According to present information, the software in the two types of receivers involved in this exercise is identical except for the tropospheric model. Differences between the "AOA tropospheric model" and the "STel tropospheric model" are, however, small, less than 1 ns [22, 23], and have no impact on this comparison.

When the local time reference produces a pulse of poor shape, differences of trigger level between the receivers can produce a differential delay. The AOA receivers use a trigger level of 0,5 V and the STel receiver a trigger level of 0,8 V. At both locations, the rise time of local references is sharp, 4 ns at the OP and less than 1 ns at the USNO. The difference in trigger level therefore has no effect on this comparison.

CONDITIONS OF COMPARISON

For the present comparison, the portable equipment took the form of the receiver, its antenna and a calibrated antenna cable. The laboratories visited supplied a) a 5 MHz reference signal, b) a series of 1 s pulses from the local reference, UTC(k), via a cable of known delay. In each laboratory the portable receiver was connected to the same clock as the local receiver and the antenna of the portable receiver was placed close to the local antenna (less than 5 meters away). The differential coordinates of the antenna phase centres were known at each site with uncertainties of a few centimetres.

During the comparisons at the Paris Observatory, before and after the visit to Washington, the receivers were programmed with 48 tracks of the *BIPM Common-View International Schedule No 22* for Europe. During the comparison at the US Naval Observatory, the receivers were programmed with the *BIPM Common-View International Schedule No 22* for East North America of 42 tracks plus 6 additional tracks. The number of programmed tracks was limited to the number allowed by the software of the AOA receivers.

During this exercise the Block II satellites were subjected to Selective Availability (SA), so strict common views were required. All common views retained for the comparison fulfilled the following conditions: 15 s common-view tolerance, 765 s minimum duration of the track, 11° minimum elevation angle for satellites. The 15 s tolerance for common views is necessitated by a fault in the AOA TTR receivers which begin observations 15 s later than scheduled. Values of the common views were computed for the midpoints of the tracks. From 34 to 40 common views were available for the comparison at each site for each full day of observations.

RESULTS

The processing of the comparison data obtained in laboratory k consists first of the computation, for each track i, of the time differences:

$$dt_{k,i}=[\mathrm{UTC(k)-GPS\ time}]_{\mathrm{BIPM5},i}-[\mathrm{UTC(k)-GPS\ time}]_{k,i}\ .$$

The noise exhibited by the time series dt_k is then analysed for each laboratory by use of the modified Allan variance. For the comparisons at the OP, at the USNO and again at

The daily results of the comparisons are as follows:

Lab	Date 1994	Number of individual common views	Mean offset /ns	Standard deviation of individual common view /ns	Standard deviation of the mean /ns
OP	May 19	18	5,95	2,72	0,64
	May 20	37	4,98	2,13	0,35
	May 21	37	5,55	1,92	0,32
	May 22	37	5,49	1,65	0,27
	May 23	40	6,07	1,99	0,31
	May 24	34	5,20	1,50	0,26
	May 25	39	4,91	2,09	0,39
	May 26	37	5,72	1,91	0,31
	May 27	38	4,96	2,19	0,35
	May 28	12	5,35	2,76	0,80
USNO	May 30	19	-7.91	1.94	0,44
	May 31	38	-7,18	2.74	0,45
	June 1	39	-7,24	3,02	0,48
	June 2	37	-8,18	3,28	0,53
	June 3	31	-8,24	2,68	0,48
OP	June 4	26	5,41	3,16	0,62
	June 5	39	5,16	2,89	0,46
	June 6	39	4,86	3,05	0,49
	June 7	39	5,52	3,08	0,49
	June 8	37	5,04	2,43	0,40
	June 9	39	5,37	2,84	0,46
	June 10	38	5,03	2,28	0,37
	June 11	35	4,78	1,70	0,29
	June 12	38	5,49	2,51	0,41
	June 13	40	6,17	2,71	0,43
	June 14	40	6,76	2,73	0,43
	June 15	18	6,85	2,03	0,48

We have computed the means of the daily values of the time differences between the portable equipment and the local equipment for the whole period of comparison at each location. We adopt the root mean squares of the residuals from the average as estimates of the confidence of the mean (1σ).

Lab	Period 1994	Total number of common views	Mean offset /ns	Estimated uncertainty /ns
OP	May 19-28	329	5,4	0,4
USNO	May 30-June 3	164	-7,8	0,5
OP	June 4-15	428	5,5	0,7

It is noticeable that the two measurements carried out at the OP, before and after the trip to the USNO, are in close agreement.

From the preceding table, it can be seen that a differential time correction should be added to GPS comparisons of the time scales kept by the laboratories visited.

$UTC(k_1)-UTC(k_2)$	Differential time correction to be added to $UTC(k_1)-UTC(k_2)$ /ns	Estimated uncertainty for the period of comparison /ns
UTC(USNO)-UTC(OP)	-13	2 (1σ)

If we suppose that the OP GPS time receiver equipment is accurately calibrated, the offset found expresses the correction to be applied to the USNO GPS equipment. If we accept that this correction concerns only the receiver, the internal delay of the USNO STel 502 receiver should be increased by 13 ns. This agrees with the result of an absolute calibration of the STel 502 receiver by the Naval Research Laboratory in 1991 [8]. According to this calibration, the internal delay of the STel 502 receiver should be increased by 14 ns.

CONCLUSION

The offset found between the two sets of GPS time receiving equipment involved in this comparison exceeds the estimated uncertainty for the period of this comparison. It also exceeds the impact of other errors expected in GPS time transfer, linked for example to the quality of tropospheric and ionospheric models, satellite ephemerides, antenna coordinates,...[4]. For this reason one might suppose that the offset of 13 ns is significant and should be taken into account. However, as shown by the results of some exercises [9,10], changes in GPS time equipment delays, apparently linked to the external temperature, do occur. These changes can reach, and even in some some circumstances excced, 10 ns. In this context the offset found in this exercise may be considered to lie within the limits of current GPS time receiver technology.

As our knowledge of the long-term behaviour of GPS time equipment delays is limited, this kind of exercise should clearly be repeated. In consequence, the results of this comparison are worthy of note, but at present, no corrections is introduced into the receivers or used in postprocessing .

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