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BUREAU INTERNATIONAL DES POIDS ET MESURES

DETERMINATION OF THE DIFFERENTIAL TIME CORRECTIONS BETWEEN GPS TIME EQUIPMENT LOCATED AT THE OBSERVATOIRE DE PARIS, PARIS, FRANCE, THE NATIONAL MEASUREMENT LABORATORY, SYDNEY, AUSTRALIA, THE ORRORAL GEODETIC OBSERVATORY, BELCONNEN, AUSTRALIA, THE MEASUREMENT STANDARDS LABORATORY, LOWER HUTT, NEW ZEALAND, AND THE COMMUNICATIONS RESEARCH LABORATORY, TOKYO, JAPAN

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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 Observatoire de Paris, Paris, France, and major time laboratories in Australia, New Zealand and Japan.

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 équipements 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 équipements GPS distants par transport d'un récepteur GPS portable. Nous rapportons ici les résultats d'un étalonnage des équipements GPS situés à l'Observatoire de Paris, Paris, France, et dans les principaux laboratoires de temps en Australie, Nouvelle Zélande et Japon.

INTRODUCTION

The method of time transfer between remote locations using GPS satellites in common view has now achieved an accuracy of several nanoseconds [1]. 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 equipment using a portable GPS time receiving equipment. Such calibrations were initiated in 1984 by the Naval Research Laboratory (NRL) with the support of the United States Naval Observatory (USNO) [2]. Since then a number of comparisons of remote GPS time receivers have taken place [3, 4]. 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 receivers have been shown to be sensitive to external temperature [5, 6, 7]. For these reasons, frequent comparisons of GPS equipment are required.

We report here the results of a calibration exercise organized under the auspices of the BIPM. Comparison of the receivers located at the Observatoire de Paris (OP), Paris, France, the National Measurement Laboratory (NML), Sydney, Australia, the Orroral Geodetic Observatory (AUS), Belconnen, Australia, the Measurement Standards Laboratory (MSL), Lower Hutt, New Zealand, and the Communications Research Laboratory (CRL), Tokyo, Japan, was effected by the means of a portable GPS time receiver BIPM3 belonging to the BIPM. This was organized as a round-trip, the portable receiver coming back to the OP after a two-month journey.

EQUIPMENT

All six receivers involved in this are single-channel, C/A-code receivers. Their principal characteristics are:

Portable receiver: BIPM3	Maker: AOA, Type: TTR6, Ser. No: 277, Adopted receiver internal delay + antenna cable delay: 290 ns.
OP:	Maker: AOA, Type: TTR5, Ser. No: 051, Antenna cable length: 33,00 m, Adopted receiver internal delay: 54 ns.

NML: Maker: AOA,
Type: TTR6,
Ser. No: 0267,
Adopted antenna cable delay: 292 ns,
Adopted receiver internal delay: 40 ns.

AUS1: Maker: TRIMBLE,
Type: TRIMBLE 5000,
Ser. No: 2903A00102,
Adopted receiver internal delay
+ antenna cable delay: 154 ns.

AUS2: Maker: FTS,
Type: FTS 8400,
Ser. No: 4058,
Adopted receiver internal delay
+ antenna cable delay: 165 ns.

MSL: Maker: DATUM Inc.,
Type:GPS Time/Freq. Monitor Model No 9390-5101,
Ser. No: D1016,
Antenna cable length: 30 m,
Adopted receiver internal delay: 101 ns.

CRL: Maker: AOA,
Type: TTR5,
Ser. No: 184,
Antenna cable length: 30,48 m,
Adopted receiver internal delay: 155 ns.

The OP receiver serves as reference for many international comparisons of GPS time equipment. It has been compared 10 times in the last 12 years with the NIST 'on line', absolutely calibrated GPS time receiver. The differences between these two receivers have always been within a few nanoseconds.

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 [1, 8]. The *Group on GPS Time Transfer Standards*, operating under the auspices of the permanent CCDS Working Group on TAI, 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 [9]. These standards are now implemented on most of AOA type GPS time receivers. In this exercise are involved receivers from three other manufacturers TRIMBLE, FTS and DATUM. We do not have sufficient information if the software of these receivers fulfill all required standards.

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. Trigger levels of TRIMBLE, FTS and DATUM receivers are unknown. Rise time of local reference is of 4 ns at the OP, 9 ns at the NML, 10 ns at the AUS, 30 ns at the MSL, and 13 ns at the CRL. The possible difference in trigger level between portable receiver and local receiver at the AUS and the MSL can have an 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. 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 trip, receivers were programmed with 48 tracks of the *BIPM GPS Common-View International Schedule No 27* for Europe. During the comparison at the NML, AUS and MSL the receivers were programmed with the *BIPM GPS Common-View International Schedule No 27* for Australia and New Zealand of 43 tracks, and at the CRL with the *BIPM GPS Common-View International Schedule No 27* for East Asia of 43 tracks.

RESULTS

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

$$dt_{k,i}=[\mathrm{UTC(k)-GPS\ time}]_{\mathrm{BIPM3},i}-[\mathrm{UTC(k)-GPS\ time}]_{k,i}\,.$$

The noise exhibited by the time series $\mathbf{dt_k}$ is then analysed by use of the modified Allan variance. For all laboratories visited it exhibits white phase noise up to an averaging interval of several days. We illustrate this in Figure 1 for the computation at the OP for a period before the trip.

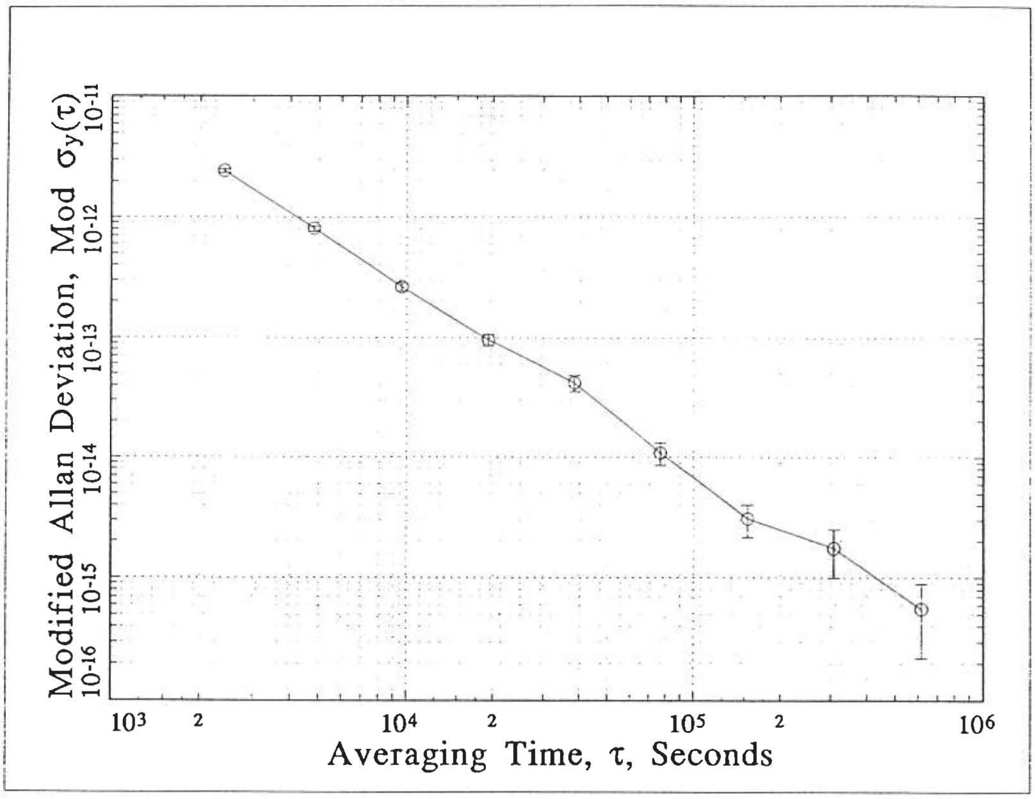

Figure 1. Square root of the modified Allan variance of the time series $\mathbf{dt_{OP}}$ for the period 3 - 18 July 1996.

This justifies computation of a mean offset for full periods of comparison at each location, and the use of the standard deviation of the mean as an expression of confidence in the mean. First, however, we computed mean offsets for one-day periods and corresponding standard deviations. Daily mean offsets permit to detect sometimes temperature dependence of the receivers.

The daily results of the comparisons are as follows:

Lab	Date 1996	Number of individual common views	Mean offset /ns	Standard deviation of individual common view /ns	Standard deviation of the mean /ns
OP	Aug 29	23	-1,61	3,46	0,72
	Aug 30	34	-2,21	3,83	0,66
	Aug 31	32	-2,03	3,53	0,62
	Sept 1	35	-2,03	3,63	0,61
	Sept 2	34	-2,38	2,79	0,48
	Sept 3	34	-2,03	3,48	0,60
	Sept 4	18	-1,61	3,50	0,83

Lab	Date 1996	Number of individual common views	Mean offset /ns	Standard deviation of individual common view /ns	Standard deviation of the mean /ns
NML	Sept 14	28	20,64	4,19	0,79
	Sept 15	29	23,48	4,52	0,84
	Sept 16	29	22,59	3,56	0,66
	Sept 17	30	22,40	2,67	0,49
	Sept 18	30	23,77	2,78	0,51
	Sept 19	30	23,50	4,61	0,84
	Sept 20	30	23,23	3,76	0,69
	Sept 21	30	24,87	4,45	0,81
	Sept 22	29	23,07	2,81	0,52
AUS1	Sept 24	17	30,35	6,56	1,59
	Sept 25	21	29,10	8,37	1,83
	Sept 26	26	32,85	8,83	1,73
	Sept 27	22	37,95	20,23	4,31
	Sept 28	26	38,12	10,53	2,06
	Sept 29	27	37,56	8,37	1,61
	Sept 30	27	36,15	4,72	0,91
AUS2	Sept 24	22	48,50	6,86	1,46
	Sept 25	29	48,00	8,77	1,63
	Sept 26	27	52,85	6,92	1,33
	Sept 27	28	48,39	5,72	1,08
	Sept 28	29	53,55	9,49	1,76
	Sept 29	29	57,59	6,3	1,17
	Sept 30	29	58,76	5,29	0,98
MSL	Oct 11	18	-35,11	7,96	1,88
	Oct 12	23	-36,30	8,64	1,80
	Oct 13	22	-39,50	10,70	2,28
	Oct 14	23	-42,22	8,13	1,70
	Oct 15	22	-36,59	10,34	2,21
	Oct 16	23	-44,96	12,59	2,62
CRL	Oct 29	29	-6,55	3,67	0,68
	Oct 30	31	-6,90	2,33	0,42
	Oct 31	31	-5,16	2,63	0,47
	Nov 01	31	-4,23	2,96	0,53
	Nov 02	30	-4,53	2,65	0,48
	Nov 03	29	-4,83	1,87	0,35
	Nov 04	30	-4,97	1,67	0,31
OP	Nov 19	15	-4,73	3,51	0,91
	Nov 20	33	-3,97	3,43	0,60
	Nov 21	33	-3,76	3,69	0,64
	Nov 22	33	-4,52	4,03	0,70

Next , we computed mean offsets for the whole periods of comparison at each location, and corresponding standard deviations. It should be noted that the standard deviation of the mean reflects only the physical conditions during the period of the comparison and gives no indication of the period-to-period reproducibility of the measurements. The results are given in the following table.

Lab	Period 1996	Total number of common views	Mean offset /ns	Standard deviation of individual common view /ns	Standard deviation of the mean /ns
OP	29 August - 4 September	210	-2,0	3,4	0,2
NML	14 - 22 September	265	23,1	3,9	0,2
AUS1	24 - 30 September	166	34,6	10,9	0,8
AUS2	24 - 30 September	193	52,5	8,2	0,6
MSL	11- 16 October	131	-39,1	10,3	0,9
CRL	29 October - 4 November	211	-5,3	2,7	0,2
OP	19 - 22 November	114	-4,2	3,7	0,3

Two repeated measurements at the OP give indication of the reproducibility of the comparisons. At the beginning and at the end of this exercise they show offsets of -2,0 ns and -4,2 ns (Table above and Figure 2). In between, the portable receiver experienced packing and unpacking, with associated vibrations and temperature changes. The possibility of changes of the delays of the local receivers is not completely excluded. It is now well documented and generally admitted that GPS time equipment is sensitive to external temperature [5,6,7].

From the preceding table, after averaging two repeated measurements at the OP, we derived differential time corrections which 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(NML)-UTC(OP)	26	3 (1σ)
UTC(AUS1)-UTC(OP)	38	10 (1σ)
UTC(AUS2)-UTC(OP)	56	10 (1σ)
UTC(MSL)-UTC(OP)	-36	10 (1σ)
UTC(CRL)-UTC(OP)	-2	3 (1σ)

Uncertainties given in the above table are conservative estimates.

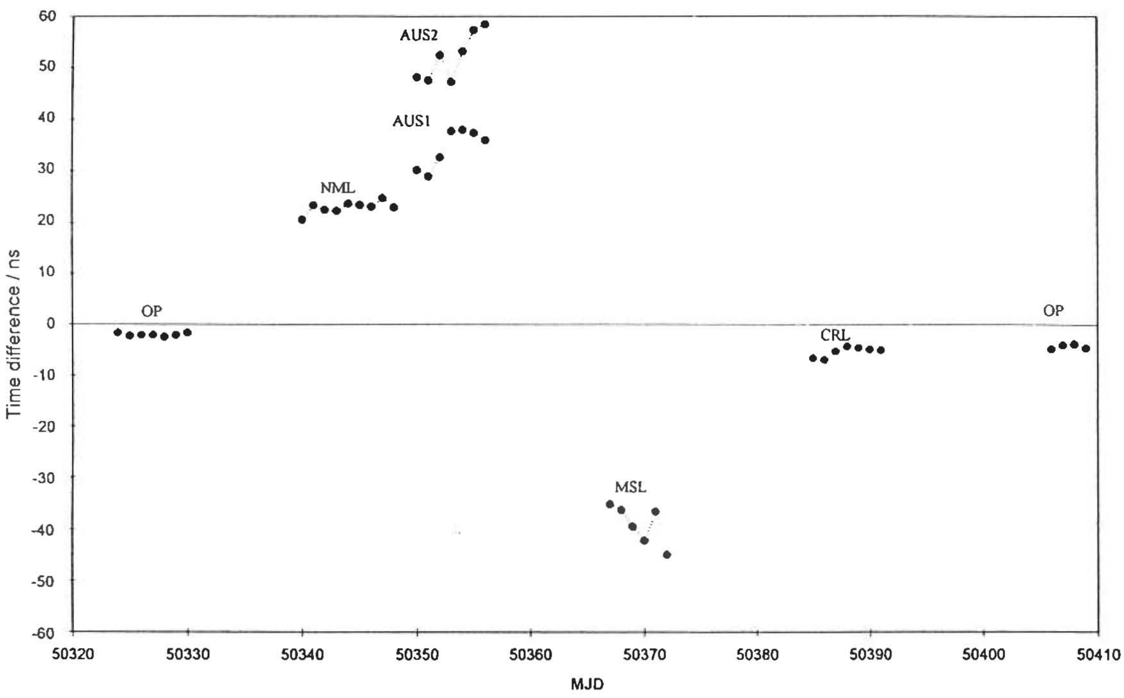

Figure 2. Daily averages of $\mathbf{dt_{k,i}}$ for each laboratory.

CONCLUSION

At the NML, the AUS and the MSL the offsets found between the GPS time receiving equipments involved in this exercise exceed the impact of errors usually expected in GPS time transfer, linked for example to the quality of determination of tropospheric and ionospheric delays, satellite ephemerides, antenna coordinates, ...[1]. For this reason these offsets are significant and should be considered to be taken into account. But, long rise times of local references associated with unknown trigger levels of the receivers at the AUS and the MSL constitute a severe limitation to the quality of the calibration at these two laboratories.

Large standard deviations and important daily variations observed at the AUS and the MSL can also be linked to the local receiver software incompatibility with standard formulae, and to possible sensitivity to environment. However, the AUS results did not show correlation with external temperature.

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