Rapport BIPM-97/5

BUREAU INTERNATIONAL DES POIDS ET MESURES

DETERMINATION OF THE DIFFERENTIAL TIME CORRECTIONS BETWEEN GPS TIME EQUIPMENT LOCATED AT THE OP, NPL, VSL, DTAG, PTB, TUG, IEN AND OCA

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Abstract

Following a suggestion during the 4th meeting of the CCDS Working Group on Two-Way Satellite Time Transfer, the BIPM decided to conduct a series of differential calibrations of GPS equipment located in European time laboratories equipped with two-way stations. Repeated calibrations of this kind should provide valuable information about the stability of GPS time equipment and serve as provisional differential calibrations of two-way equipment. This report concerns the first of these exercises. It took place from 30 May to 4 August 1997 and consisted in the transport of a portable GPS time receiver from one location to another, according to a round trip involving eight laboratories in Europe.

Resumé

Suivant une suggestion exprimée lors de la 4e réunion du Groupe de travail du CCDS sur les comparaisons d'horloges par aller et retour sur satellite, le BIPM a décidé de conduire une série d'étalonnages différentiels des équipements de réception du temps du GPS, situés dans des laboratoires de temps européens équipés de stations bidirectionnelles. Des étalonnages répétés de ce type devraient fournir de précieuses informations sur la stabilité des équipements GPS et servir d'étalonnages différentiels provisoires aux équipements bidirectionnels. Ce rapport concerne la première de ces campagnes. Elle a eu lieu entre le 30 mai et le 4 août 1997 et a consisté à transporter un récepteur du temps du GPS d'un site à l'autre selon une boucle fermée qui a impliqué huit laboratoires en Europe.

INTRODUCTION

Following a suggestion during the 4th meeting of the CCDS Working Group on Two-Way Satellite Time Transfer [1], the BIPM decided to conduct a series of differential calibrations of GPS equipment located in seven European time laboratories equipped with two-way stations [2, 3]: the National Physical Laboratory (NPL), Teddington, United Kingdom, the NMi Van Swinden Laboratorium (VSL), Delft, the Netherlands, the Deutsche Telekom AG (DTAG), Darmstadt, Germany, the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany, the Technical University (TUG), Graz, Austria, the Istituto Elettrotechnico Nazionale Galileo Ferraris (IEN), Torino, Italy, and the Observatoire de la Côte d'Azur (OCA), Grasse, France.

It was decided to use GPS time equipment located at the Observatoire de Paris (OP), Paris, France, as reference. To check the reproducibility of the measurements, the exercises are organised as round-trips beginning and ending at the OP. Although the OP is not equipped with a two-way station, it serves as pivot laboratory for GPS links used for TAI computation. The OP receiver serves also as reference for many international comparisons of GPS time equipment. It has been compared ten times in the last twelve years with the NIST 'on line', absolutely-calibrated GPS time receiver. The differences between these two receivers have always been within a few nanoseconds.

Repeated determinations of the differential time corrections between GPS time equipment located in the visited laboratories should:

- improve accuracy of involved GPS time links,
- provide valuable information about the stability of GPS time equipment,
- serve as provisional differential calibrations of the two-way equipment.

This report details the first of these exercises. It took place from 30 May to 4 August 1997. The following ones are scheduled at four-five months intervals.

EQUIPMENT

All the receivers involved in this comparison are single-channel, C/A code, 0.5 V trigger level, NBS type receivers. Their principal characteristics are:

OP:	Maker: Allen Osborne Associates, Type: NBS/TTR5, Receiver Ser. No: 051, Internal delay: 54 ns.
NPL:	Maker: Allen Osborne Associates, Type: NBS/TTR5A, Receiver Ser. No: 276.
VSL:	Maker: VSL, Type: NBS/TTR5, Receiver Ser. No: 01.
DTAG:	Maker: VSL, Type: NBS, Receiver Ser. No: 19.
PTB:	Maker: Rockwell Collins, Type: NBS/TTR5.
TUG:	Maker: NBS, Type: NBS, Receiver Ser. No: 03.
OCA:	Maker: Allen Osborne Associates, Type: NBS/TTR5, Receiver Ser. No: 053.
Portable receiver: BIPM3	Maker: Allen Osborne Associates, Type: NBS/TTR6, Receiver Ser. No: 277,

As all of the receivers involved in this exercise use identical software of NBS type, any imperfection of this software cancels during zero-baseline comparison. Main source of errors remains hardware variations.

At the beginning of the trip, the portable BIPM3 receiver was equipped with an antenna cable measured at the BIPM:

- portable IF (Intermediate Frequency) antenna cable C3: 232.1 ns, uncertainty of 0.40 ns (1 σ).

To measure cable delays at the BIPM we used the pulse method with a time intervallometer steered by an external frequency source, an HP 5071A clock. We measured at the very beginning of the linear part of the rising pulse at each end of the cable using a 0.5 V trigger level [4].

During the visit to the VSL the above values were compared to a group delay measurement using the MITREX modem at 70 MHz [4]:

- portable IF antenna cable C3: 231.45 ns , uncertainty of 0.07 ns (1 σ).

The VSL measurement differs from the one of BIPM by about 2 σ and may reveal the limited accuracy of BIPM measurement. However, any imperfection in the delay measurement of portable equipment, if remaining constant throughout the trip, cancels during determination of differential time corrections between laboratories involved.

But, on return to the OP, connector at the antenna end of the portable IF antenna cable was found to be detached (the connector just fell off the cable). The cable was probably twisted as it was packed and unpacked in the different laboratories. This portable C3 cable is about five years old and has served on several calibration trips, so its age may also have been a factor. On future calibration trips we shall consider using the cables supplied by the laboratories visited; alternatively more care must be taken during cable manipulation. For long trips, another alternative is that we always use a fresh cable.

Because of this mishap we replaced the BIPM IF C3 with the BIPM IF C1 cable for measurements at the OP after the trip. To measure the delay of the cable we used as before the pulse method:

- portable IF antenna cable C1: 235.5 ns, uncertainty of 0.40 ns (1 σ).

The use of different cable for the measurement at the OP after the trip, introduces an additional source of uncertainty which must be taken into account for the determination of total uncertainty for this calibration.

Cables used during the trip to connect portable receiver in the laboratories visited are specified in Annex I.

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 the receivers were programmed with the *BIPM Common-View International Schedule No 28* for Europe.

RESULTS

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

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

The noise exhibited by the time series dt_k is then analysed, for each of the laboratories visited, by use of the modified Allan variance. In each case, this exhibits white phase noise up to an averaging interval of about one day. We illustrate this in Figure 1 which shows computation for the OP over a period following the trip.

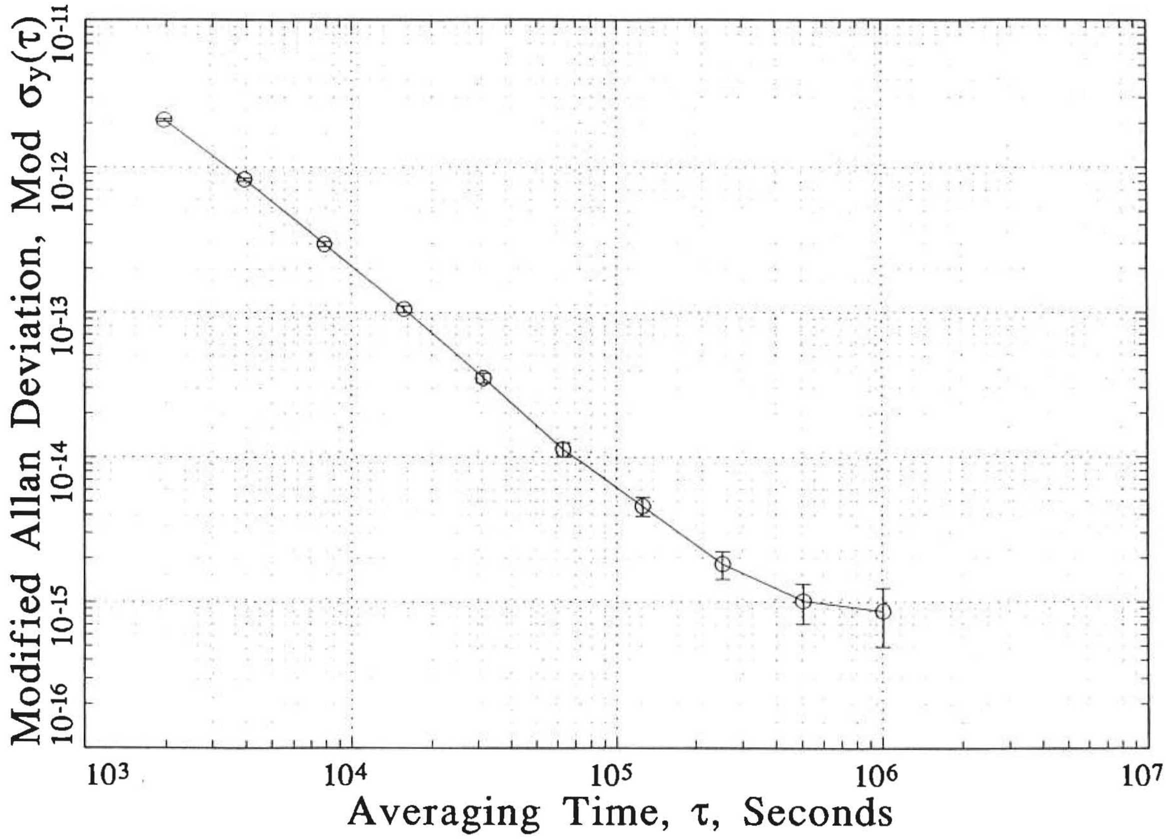

Figure 1. Square root of the modified Allan variance of the time series dt_{OP} for the period July 29 - September 29, 1997.

The one-day averages are reported in Figure 2 and Annex II. The level of noise for one-day period is reported in Table 1.

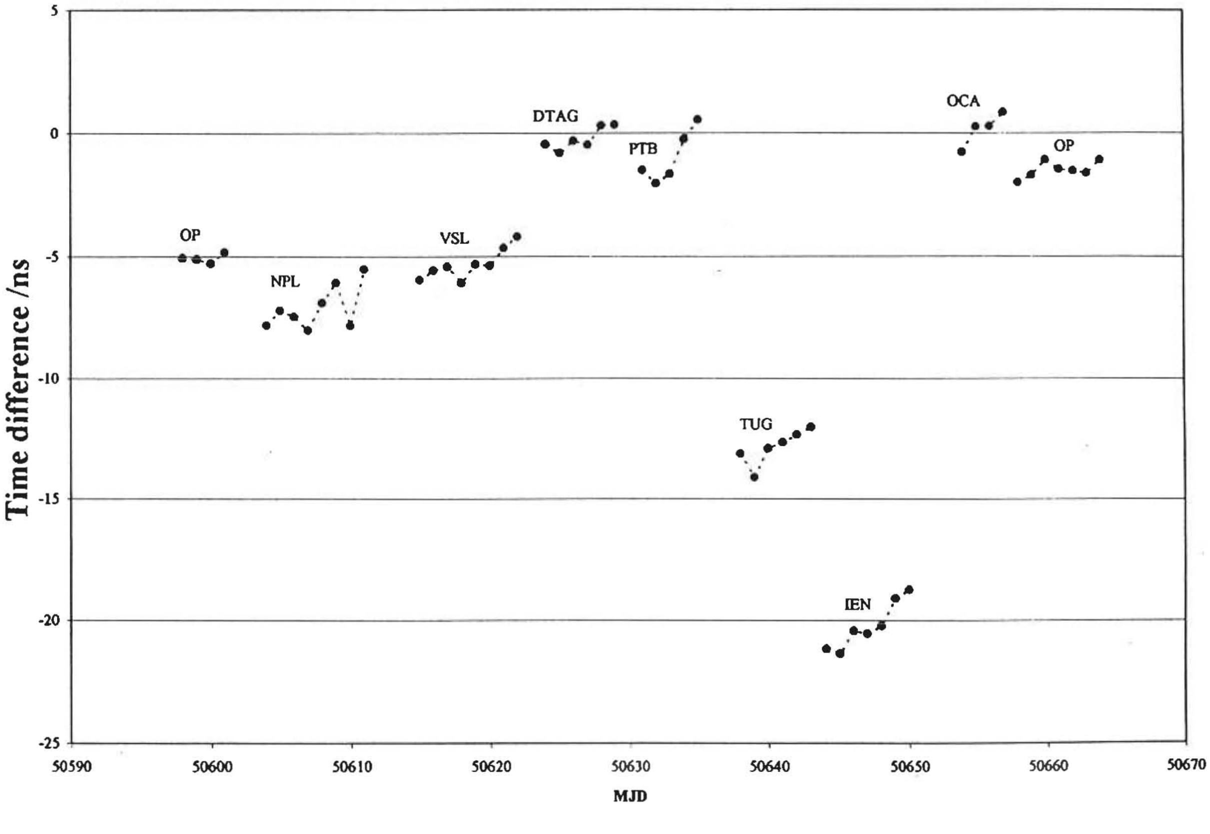

Figure 2. Daily averages of $dt_{k,i}$ for each laboratory.

The one-day averages exhibit systematic effects which we characterised by dispersion of daily means provided also in Table 1. These systematic effects are due to the hardware instability often linked to the sensitivity of GPS time equipment to environmental conditions [5,6,7].

Next, we computed mean offsets for the full duration of comparison at each location, and the corresponding standard deviations of individual common view (Table 1).

Table 1. Mean offsets for the full duration of comparison at each location.

Lab	Period 1997	Total number of common views	Mean offset /ns	Standard deviation of individual common view /ns	Level of noise for 1 day /ns	Dispersion of daily mean /ns
OP	30 May - 2 June	120	-5.1	1.8	0.3	0.2
NPL	5-12 June	230	-7.1	3.4	0.5	0.9
VSL	16-23 June	293	-5.3	2.3	0.4	0.6
DTAG	25-30 June	207	-0.2	2.0	0.3	0.5
PTB	2-6 July	206	-1.0	2.6	0.3	1.1
TUG	9-14 July	219	-12.8	1.8	0.3	0.7
IEN	15-22 July	245	-20.3	2.3	0.3	1.0
OCA	25-28 July	112	+0.2	2.5	0.4	0.7
OP	29 July - 4 Aug	291	-1.5	2.3	0.3	0.3

The repeated measurements at the OP give an indication of the reproducibility of the comparisons. At the beginning and at the end of this exercise they show offsets of -5.1 ns and -1.5 ns (Table 1 and Figure 2). In between (60 days), the portable receiver was packed and unpacked, with associated vibrations and temperature changes. Changes of a few nanoseconds in differential delays between local and portable receivers were observed during calibration in several visited laboratories (Figure 2). The possibility that changes occurred also in the delay of the OP receiver is not excluded. It is now well documented, and generally admitted, that GPS time equipment is sensitive to external temperatures [5, 6, 7].

From the preceding table, after averaging the two measurements at the OP, we derived differential time corrections which should be added to the values derived during the GPS comparisons of the time scales kept by the laboratories visited (Table 2).

Table 2. Differential time corrections to be added to[*UTC*(k_1)-*UTC*(k_2)].

[*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*(NPL)-*UTC*(OP)]	-4	3 (1 σ)
[*UTC*(VSL)-*UTC*(OP)]	-2	3 (1 σ)
[*UTC*(DTAG)-*UTC*(OP)]	+3	3 (1 σ)
[*UTC*(PTB)-*UTC*(OP)]	+2	3 (1 σ)
[*UTC*(TUG)-*UTC*(OP)]	-10	3 (1 σ)
[*UTC*(IEN)-*UTC*(OP)]	-17	3 (1 σ)
[*UTC*(OCA)-*UTC*(OP)]	+4	3 (1 σ)

The uncertainties given in this table are conservative. They are mainly driven by the uncertainty due to the 'round-trip' reproducibility at the OP, but some other elements are important, especially the effect of the change of the portable antenna cable and noise of receivers at each location.

CONCLUSION

This was the first of a series of BIPM differential calibrations of GPS time equipment located in time laboratories equipped with two-way stations. For some laboratories the data obtained confirm, to within their uncertainties, differential time corrections determined in the past. For other laboratories differences exceed the uncertainties. The earlier trips, however, were made some time ago, in one case eleven years ago. In the interim natural changes in the hardware occurred, pieces of equipment may also have been changed. For this reason consistency of the calibrations was not to be expected. The present series of calibrations, repeated every four or five months, should allow more rigorous checks of the delay stability of GPS time equipment.

The results of this exercise should provide a provisional differential calibration for two-way equipment.

Acknowledgements

The authors wish to express their gratitude to their colleagues from visited laboratories for full collaboration without which this work could not have been accomplished.

REFERENCES

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Annex I

Cables used to connect portable receiver in the laboratories visited

Laboratory	IF antenna cable	LO antenna cable	Local UTC cable
OP (before trip)	BIPM C3 [2]	BIPM C2 [4]	OP cable of 315 ns [1]
NPL	BIPM C3 [2]	BIPM C2 [4]	NPL cable of 42 ns
VSL	VSL cable No 9 of 649.49 ns [3]	VSL cable No 10	VSL cable of 6 ns [2]
DTAG	DTAG cable No 22 of 486 ns [2]	DTAG cable No 24	DTAG cable of 123 ns [2]
PTB	BIPM C3 [2]	BIPM C2 [4]	PTB cable of 20 ns [2]
TUG	BIPM C3 [2]	BIPM C2 [4]	TUG cable of 108 ns [2]
IEN	BIPM C3 [2]	BIPM C2 [4]	IEN cable of 13 ns [2]
OCA	BIPM C3 [2]	BIPM C2 [4]	OCA cable of 93 ns [2]
OP (after trip)	BIPM C1 [2]	BIPM C2 [4]	OP cable of 315 ns [1]

[1] Measured by dual weighting method with uncertainty of 0.3 ns (1 σ).

[2] Measured by pulse method with 0.5 V trigger level with uncertainty of 0.4 ns (1 σ).

[3] Group delay measurement using the MITREX modem at 70 MHz with uncertainty of 0.07 ns (1 σ).

[4] C2: BIPM LO antenna cable of about 47 m length.

Annex II

Daily results of the comparisons

Lab	Date 1997	Number of individual common views	Mean offset /ns	Standard deviation of individual common view /ns	Standard deviation of the mean /ns
OP	May 30	19	-5.04	1.45	0.33
	May 31	46	-5.10	1.69	0.25
	June 1	45	-5.27	2.16	0.32
	June 2	10	-4.82	1.99	0.63
NPL	June 5	28	-7.78	2.88	0.54
	June 6	28	-7.18	3.85	0.73
	June 7	27	-7.43	1.82	0.35
	June 8	28	-7.99	2.43	0.46
	June 9	30	-6.88	4.09	0.75
	June 10	29	-6.04	4.01	0.75
	June 11	30	-7.80	2.52	0.46
	June 12	30	-5.50	4.08	0.74
VSL	June 16	18	-5.94	2.55	0.60
	June 17	44	-5.55	2.39	0.36
	June 18	43	-5.40	2.32	0.35
	June 19	41	-6.06	1.82	0.29
	June 20	43	-5.30	2.34	0.36
	June 21	43	-5.37	2.37	0.36
	June 22	41	-4.65	2.07	0.32
	June 23	20	-4.20	1.95	0.44
DTAG	June 25	17	-0.45	1.63	0.39
	June 26	41	-0.79	1.94	0.30
	June 27	41	-0.32	2.50	0.39
	June 28	38	-0.47	2.04	0.33
	June 29	30	0.30	1.82	0.33
	June 30	40	0.34	1.66	0.26
PTB	July 2	18	-1.48	2.72	0.64
	July 3	44	-2.03	2.16	0.33
	July 4	49	-1.65	2.74	0.39
	July 5	47	-0.26	2.22	0.32
	July 6	48	0.54	2.50	0.36

Lab	Date 1997	Number of individual common views	Mean offset /ns	Standard deviation of individual common view /ns	Standard deviation of the mean /ns
TUG	July 9	18	-13.12	1.21	0.28
	July 10	48	-14.11	1.76	0.25
	July 11	47	-12.90	1.64	0.24
	July 12	45	-12.64	1.56	0.23
	July 13	47	-12.32	1.78	0.26
	July 14	14	-12.01	1.61	0.43
IEN	July 15	12	-21.16	2.42	0.70
	July 16	44	-21.36	2.19	0.33
	July 17	44	-20.42	2.14	0.32
	July 18	43	-20.54	1.73	0.26
	July 19	43	-20.22	2.09	0.32
	July 20	44	-19.10	2.32	0.35
	July 22	15	-18.73	2.90	0.75
OCA	July 25	14	-0.76	3.24	0.87
	July 26	44	0.25	2.51	0.38
	July 27	41	0.27	2.19	0.34
	July 28	13	0.85	2.37	0.66
OP	July 29	27	-2.00	2.77	0.53
	July 30	46	-1.69	2.28	0.34
	July 31	40	-1.08	2.25	0.36
	Aug 1	44	-1.46	1.97	0.30
	Aug 2	42	-1.52	1.97	0.30
	Aug 3	46	-1.62	2.66	0.39
	Aug 4	46	-1.08	2.52	0.37