Rapport BIPM-2004/05

BUREAU INTERNATIONAL DES POIDS ET MESURES

DETERMINATION OF THE DIFFERENTIAL TIME CORRECTIONS FOR GPS TIME EQUIPMENT LOCATED AT THE OP, NPL, IEN, PTB, and VSL

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Abstract

Following a suggestion at the 4th meeting of the CCTF Working Group on Two-Way Satellite Time Transfer (TWSTFT), the BIPM is conducting a series of differential calibrations of GPS equipment located in time laboratories equipped with two-way stations. This report details measurements which took place from 14 May to 15 July 2003, involving GPS time equipment located at the Observatoire de Paris (OP, Paris, France), the National Physical Laboratory (NPL, Teddington, United Kingdom), the Istituto Elettrotecnico Nazionale Galileo Ferraris (IEN, Turin, Italy), the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany), and the Van Swinden Laboratorium (VSL, Delft, the Netherlands). The dates of this GPS calibration for IEN and PTB have been chosen to follow the dates of TWSTFT calibration between these two laboratories scheduled for 30 May - 6 June 2003.

INTRODUCTION

Following a suggestion at the 4th meeting of the CCTF Working Group on TWSTFT [1], the BIPM is conducting a series of differential calibrations of GPS equipment located in time laboratories equipped with two-way stations [2, 3].

As previously, the GPS time equipment located at the OP was chosen as reference. To check the reproducibility of the measurements, the calibrations were organized as round trips beginning and ending at the OP. Over the last twenty years, the OP's GPS time receiver has been compared several times with the NIST absolutely-calibrated reference GPS time receiver. The difference between these two has never exceeded a few nanoseconds.

Repeated determinations of the differential time corrections for the GPS time equipment located in the various laboratories should:

- improve the accuracy of the access to UTC of participating laboratories;
- provide valuable information about the stability of GPS time equipment;
- serve as provisional differential calibrations of the two-way equipment at the laboratories.

This report details an exercise which took place from 14 May to 15 July 2003. The dates of this GPS calibration for IEN and PTB have been chosen to follow the dates of TWSTFT calibration between these two laboratories scheduled for 30 May - 6 June 2003.

EQUIPMENT

Details of the receivers involved are provided in Table 1. More information about the set-up of equipment at each location is provided in Appendix I.

Table 1. GPS equipment involved in this comparison.

Laboratory	Receiver Maker	Receiver Type	Receiver Ser. No.
OP	AOA	TTR-5	NBS051
NPL	TFS	TFS receiver	TFS 101
IEN	3S Navigation	GNSS-300T	1003
PTB	AOA	TTR-5A	0156
VSL	VSL	NBS-type	VSL01
BIPM Portable receiver	AOS	TTS-2	028

The portable BIPM receiver is equipped with a C123 cable. Its delay measured at the BIPM is 178.78 ns with a standard deviation of 0.4 ns.

This delay was measured using a double-weight pulse method with a time interval counter steered by an external frequency source (an Active Hydrogen Maser CH1-75, KVARZ). We measured at the beginning of the linear part of the rising pulse at each end of the cable using a 0.5 V trigger level [4].

The delay of this cable was also measured at the laboratories visited. The results are reported in Appendix II.

CONDITIONS OF COMPARISON

For the present comparison, the portable equipment comprised the receiver, its antenna, and a calibrated antenna cable. The laboratories visited supplied: (a) a 10 MHz reference signal; and (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 standard uncertainties (1σ) of a few centimetres.

RESULTS

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

$$\mathrm{d}t_{k,i} = [UTC(k) - GPS\ time]_{\mathrm{BIPM},i} - [UTC(\mathrm{k}) - GPS\ time]_{k,i}\ .$$

The noise exhibited by the time series $\mathrm{d}t_k$ is then analysed, for each of the laboratories visited, by use of the modified Allan variance. In each case, white phase noise was exhibited up to an averaging interval of about one day. We illustrate this in Figure 1.

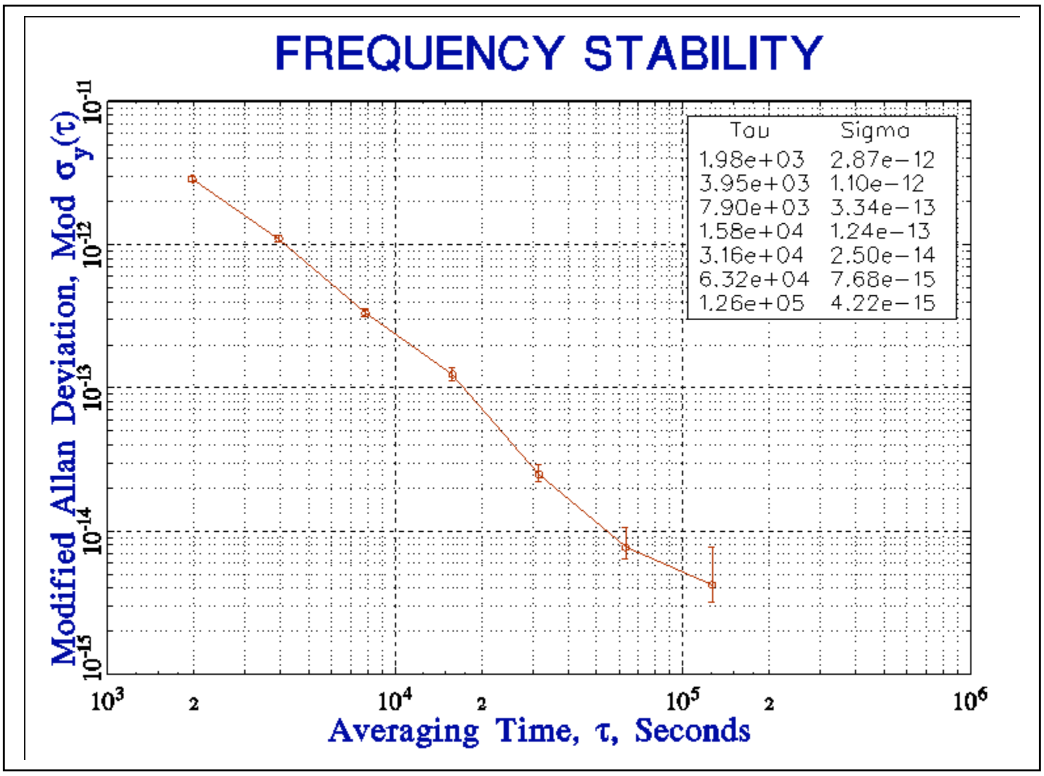


Figure 1. Square root of the modified Allan variance of the time series $\mathrm{d}t_{\mathrm{OP}}$ for the period: 07 July 2003 to 15 July 2003.

The one-day averages are reported in Figure 2 and Appendix III. The level of noise for one-day averaging period is reported in Table 2.

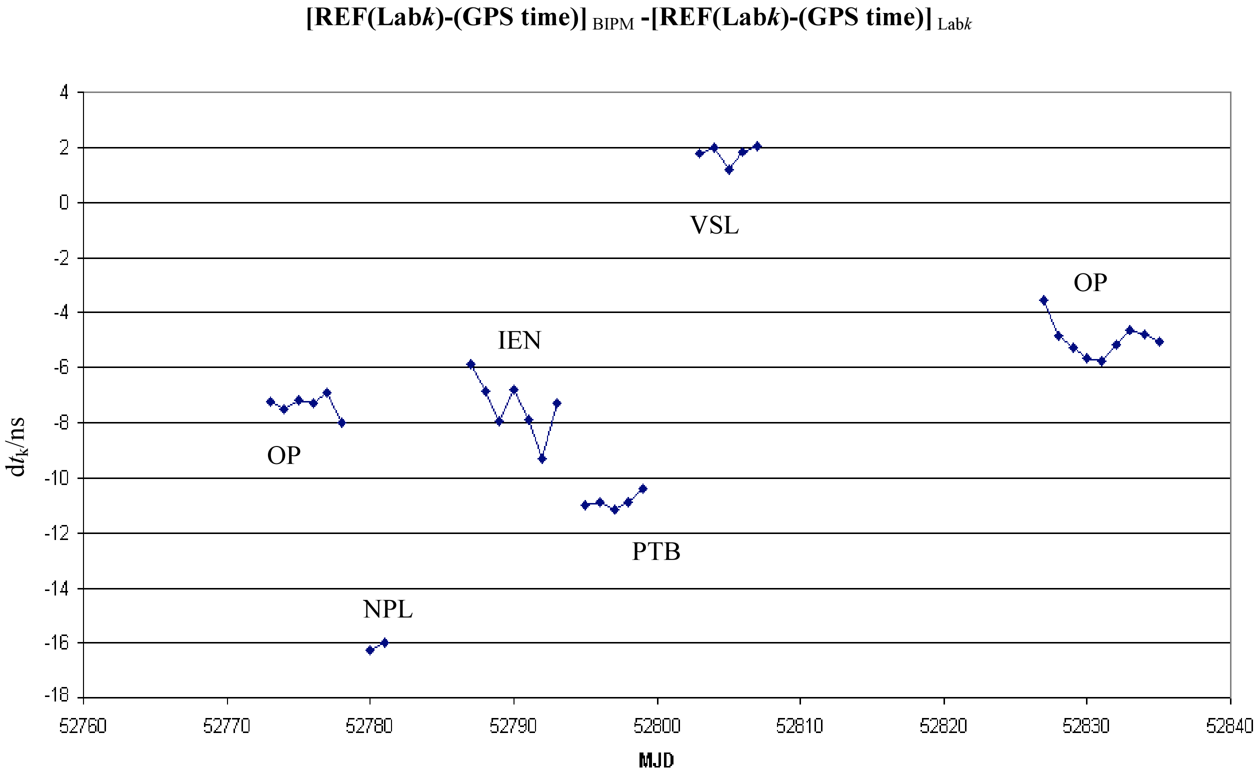


Figure 2. Daily averages of $dt_{k,i}$ for each laboratory k (see Appendix III).

Next, we computed mean offsets for the full duration of comparison at each location, and the corresponding standard deviations of individual common view measurements (see Table 2).

Table 2. Mean offsets for the full duration of the comparison at each location.

Lab	Period 2003	Total number of common views	Mean offset /ns	Standard deviation of individual common view observations /ns	Level of noise for 1 day /ns	Dispersion of daily mean /ns
OP	14 – 18 May	198	-7.2	2.6	0.3	0.4
NPL	21 – 22 May	433	-16.1	2.5	0.2	0.2
IEN	28 May– 3 June	2955	-7.6	2.7	0.8	1.1
PTB	5 – 7 June	192	-10.8	4.2	0.4	0.3
VSL	13 – 17 June	150	1.7	2.9	0.4	0.3
OP	7 – 15 July	350	-5.0	3.3	0.5	0.7

The “closure” – the difference between the first and last sets of measurements made at the OP – was within an acceptable range. After averaging the results of the two sets of measurements at the OP, we then derived differential time corrections which should be made (added) to time differences derived during the GPS comparisons of the time scales kept by the laboratories. The results are summarized in Table 3.

Table 3. Differential time correction d to be added to$[UTC(k_1) - UTC(k_2)]$, and its estimated uncertainty $u(d)$ for the period of comparison (1σ).

$[UTC(k_1)$-$UTC(k_2)]$	d/ns	$u(d)$/ns
[*UTC*(NPL)-*UTC*(OP)]	-10.1	3.0
[*UTC*(IEN)-*UTC*(OP)]	-1.5	3.0
[*UTC*(PTB)-*UTC*(OP)]	-4.7	3.0
[*UTC*(VSL)-*UTC*(OP)]	+7.8	3.0

The uncertainties given in this table are conservative. They are mainly driven by the uncertainty due to the ‘round-trip’ reproducibility at the OP.

CONCLUSION

These measurements are part of a series of differential calibrations of GPS equipment located in time laboratories equipped with TWSTFT stations. They provide an independent calibration of TWSTFT equipment and also improve the accuracy of the access to UTC of the participating laboratories.

The present measurements were performed under good conditions. The GPS time equipment of most of the participating laboratories agrees within a few nanoseconds with the reference equipment at the OP. Only at the NPL does the difference with the OP reach 10 ns, largely exceeding the estimated uncertainty. In this laboratory, readjustment of the delay of GPS time equipment might be considered. It should be stressed that the NPL is linked to the UTC system through the NPL/PTB TWSTFT link, which was calibrated by GPS. Should this TWSTFT link be recalibrated with results of this calibration trip? The GPS common-view for this link is used as a back-up technique for NPL/PTB.

The next series of such measurements involving the same laboratories is scheduled for 2004.

Acknowledgements

The authors wish to express their gratitude to their colleagues for the unreserved collaboration they have received. Without this help, the work could not have been accomplished.

REFERENCES

[1] The CCDS Working Group on Two-Way Satellite Time Transfer, *Report of the 4th Meeting*, Turin, October 1996.

[2] J.A. Davis, P.R. Pearce, D. Kirchner, H. Ressler, P. Hetzel, A Söring, G. De Jong, F. Baumont, L. Veenstra, "Two-Way Satellite Time Transfer Experiments Between Six European Laboratories Using the INTELSAT (VA-F13) Satellite", *Proc. 8th EFTF*, pp. 296-314, March 1994.

[3] D. Kirchner, H, Ressler, R. Robnik, "Recent work in the field of two-way satellite time transfer carried out at the TUG", *Proc. 11th EFTF*, pp. 205-208, March 1997.

[4] G. de Jong, "Measuring the propagation time of coaxial cables used with GPS receivers," *Proc. 17th PTTI,* pp. 223-232, December 1985.

Appendix I

Set-ups of local and portable equipment at each location (forms completed by the participating laboratories)

BIPM GPS calibration information sheet

Laboratory:	BNM – SYRTE, Observatoire de Paris
Date and hour of the beginning of measurements:	14 May 2003
Date and hour of the end of measurements:	19 May 2003

Receiver setup information

	Local: NBS 51	**Portable: BIPM K**
• Maker:	Allen Osborne Associates	AOS
• Type:	TTR-5	TTS-2
• Serial number:	051	S/N 028
• Receiver internal delay (GPS) :	54 ns	0.0 (not calibrated)
• Receiver internal delay (GLO) :	-	-
• Antenna cable identification:	505 IF	C123
Corresponding cable delay :	168 ns ± 0.3 ns	178.78 ns ± 0.4 ns
• UTC cable identification:	503	497
Corresponding cable delay :		-
Delay to local UTC :	304 ns	306 ns
• Receiver trigger level:	0.5 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF
Latitude or X m	4 202 780.30 m	4 202 781.970 m
Longitude or Y m	171 370.03 m	171 364.125 m
Height or Z m	4 778 660.12 m	4 778 658.526 m

Antenna information

	Local:	**Portable:**
• Maker:	A.O.A.	ITR TSA-2
• Type:	-	GPS
• Serial number:	-	3-072002
If the antenna is temperature stabilised		
• Set temperature value :	-	-

Local antenna cable information

• Maker:	/
• Type:	RG-58
• Is it a phase stabilised cable:	No
• Length of cable outside the building :	Approximately 6 meters

General information

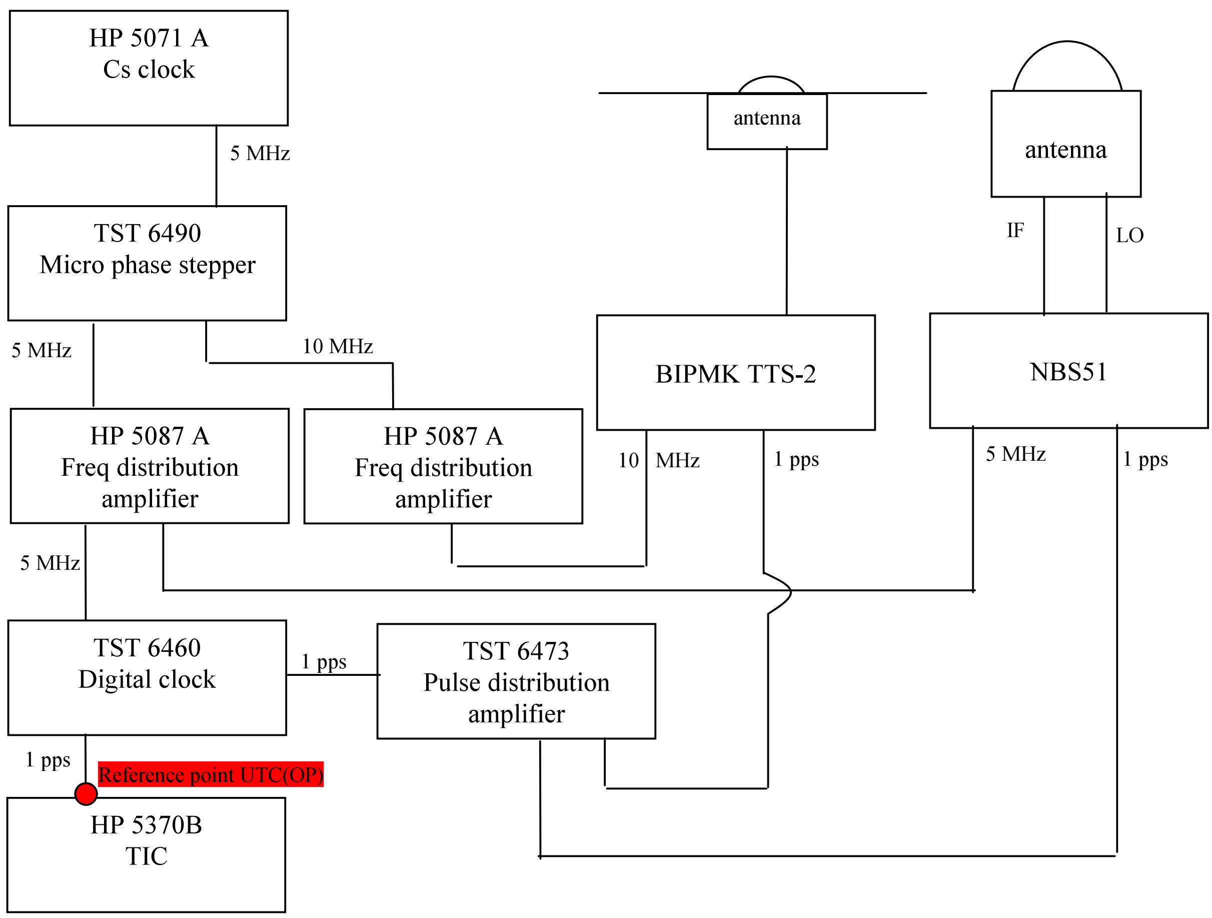
• Rise time of the local UTC pulse:	4 ns
• Is the laboratory air conditioned:	Yes
• Set temperature value and uncertainty :	(21.5 ± 2) °C
• Set humidity value and uncertainty :	/

Cable delay control

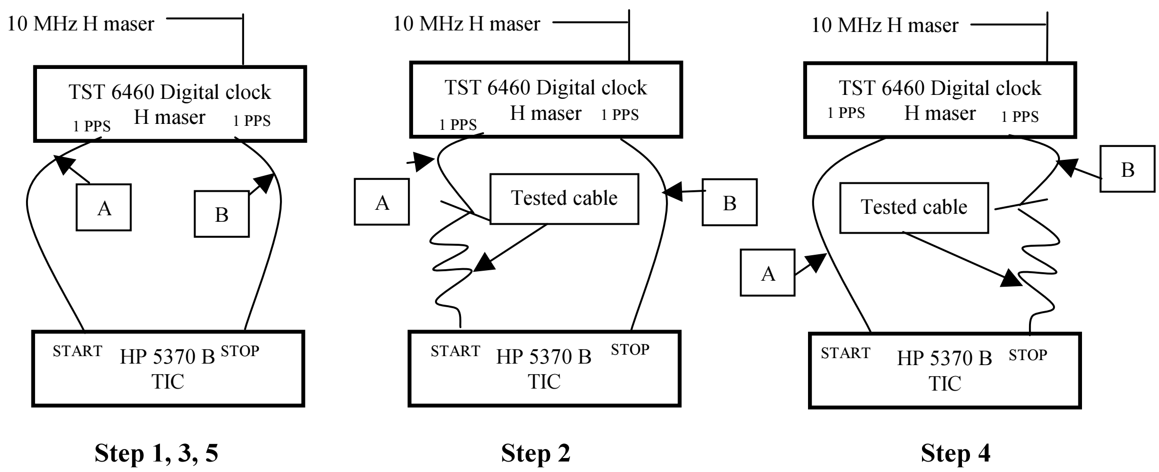
Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C123	178.78 ns ± 0.4 ns	179.9 ns ± 0.3 ns

Plot of the experiment set-up:

Link to the local UTC of both receivers and Antenna positions



Description of the local method of cable delay measurement:



The method used to calibrate the cables is a double wheight method in five steps as shown above.
At each step (i) the TIC gives the result (R_i)of 100 measurements.
The test cable delay is then obtained by the following formula:

$$\text{Delay} = \frac{R_2 - \left(\frac{R_1 + R_3}{2}\right) + \left(\frac{R_3 + R_5}{2}\right) - R_4}{2} + \text{corrections}$$

The corrections are the estimated delay introduced by adaptators : - 0.1 ns / adaptator

BIPM GPS calibration information sheet

Laboratory:	IEN G. Ferraris – Turin (Italy)
Date and hour of the beginning of measurements:	2003-28-05 (MJD: 52787) - 14:46 UTC
Date and hour of the end of measurements:	2003-03-06 (MJD: 52793) - 07:26 UTC

Receiver setup information

	Local:	Portable: BIPM K
• Maker:	3S Navigation	AOS
• Type:	GNSS-300T	TTS-2
• Serial number:	1003	S/N 028
• Receiver internal delay (GPS) :	1693.0 ns (*) (receiver + cable)	0.0 (not calibrated)
• Receiver internal delay (GLO) :	3600.0 ns	-
• Antenna cable identification:	-	C123
Corresponding cable delay :	Not available	178.78 ns ± 0.4 ns
• UTC cable identification:	1PPS(3SN)	1PPS(BIK)
Corresponding cable delay :	not available	
Delay to local UTC :	(5.1 ± 0.3) ns	(3.3 ± 0.3) ns
• Receiver trigger level:	0.5 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF
Latitude or X m	45 00 53.987	45 00 54.048 N
Longitude or Y m	007 38 20.686	007 38 20.709 E
Height or Z m	306.64 m	306.64 m

Antenna information

	Local:	Portable:
• Maker:	3S navigation	ITR TSA-2
• Type:	-	GPS
• Serial number:	-	3-072002
If the antenna is temperature stabilised		
• Set temperature value :	-	

Local antenna cable information

• Maker:	Mantovani & Serazzi - Italy
• Type:	RG 58 Cu
• Is it a phase stabilised cable:	no
• Length of cable outside the building :	5 m

General information

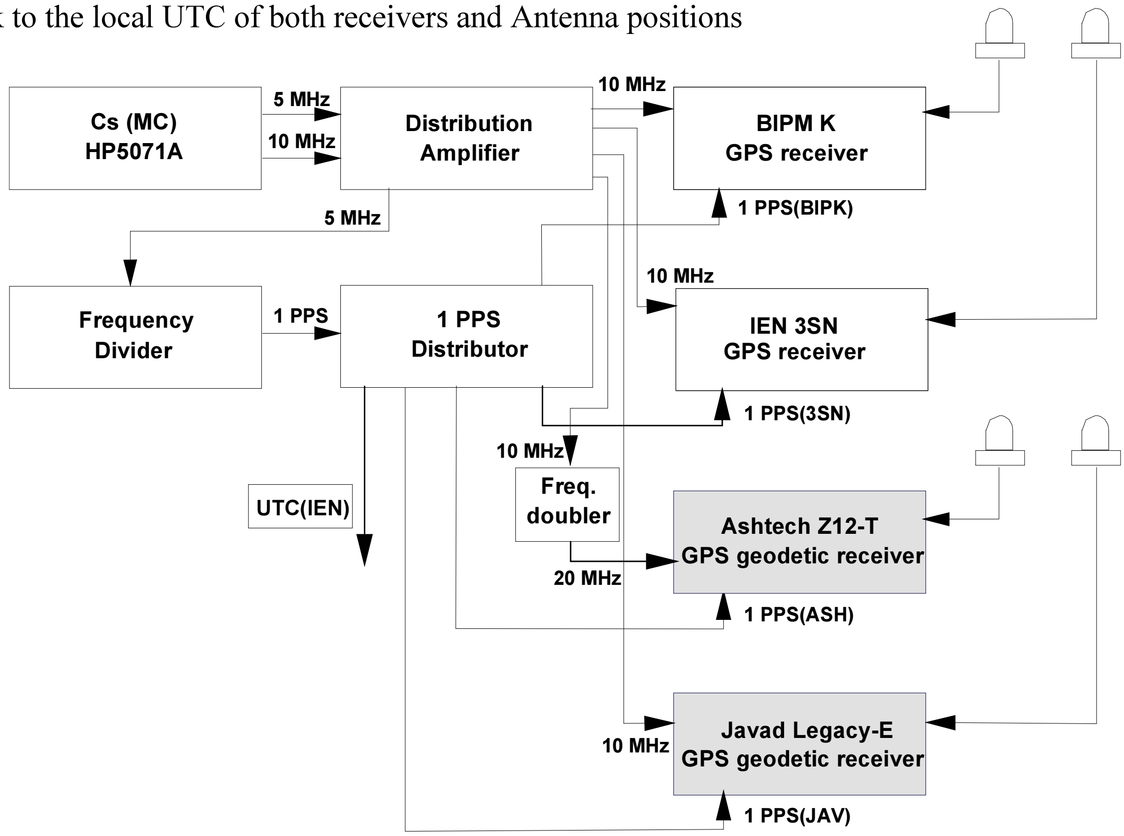
• Rise time of the local UTC pulse:	15 ns
• Is the laboratory air conditioned:	yes
• Set temperature value and uncertainty :	(23±1) °C
• Set humidity value and uncertainty :	(48±10) %

Cable delay control

Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C123	178.78 ns ± 0.4 ns	(181.0±0.3) ns

Plot of the experiment set-up:

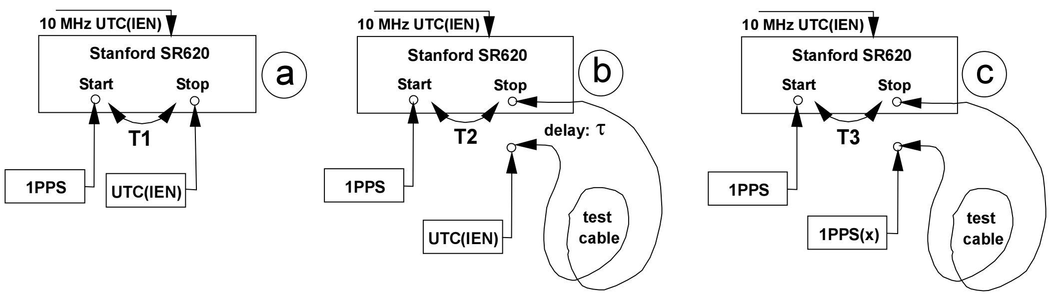
Link to the local UTC of both receivers and Antenna positions



Measured delays:

UTC(IEN) – 1PPS(BIK) = (3.3 ± 0.3) ns
UTC(IEN) – 1PPS(3SN = (5.1 ± 0.3) ns
UTC(IEN) – 1PPS(ASH) = (362.8 ± 0.3) ns + (10.6 ± 0.3) ns
10.6 ns is the Ashtech "1PPS – 20 MHz" internal delay
UTC(IEN) – 1PPS(JAV) = (362.8 ± 0.3) ns

Description of the local method of cable delay measurement:



Delay measurements: differential method to compensate for the counter asymmetry.
1PPS: auxiliary UTC(IEN) time reference.
1PPS(x): 1PPS(BIPK), 1PPS(3SN), 1PPS(ASH) or 1PPS(JAV)
T1, T2 and T3: mean value of 20 delay measurements (with estimation of the standard deviation).
τ: delay of an auxiliary cable (test cable) or of the BIPM antenna cable.

τ = T2 – T1 **UTC(IEN) – 1PPS(x) = T3 – T2**

BIPM GPS calibration information sheet

Laboratory:	PTB
Date and hour of the beginning of measurements:	2003-06-05 13:00 UTC
Date and hour of the end of measurements:	2003-06-10 05:00 UTC

Receiver setup information

	Local:	Portable: BIPM K
• Maker:	AOA	AOS
• Type:	TTR-5A	TTS-2
• Serial number:	S/N 0156	S/N 028
• Receiver internal delay (GPS) :	58.0 ns	0.0 (not calibrated)
• Receiver internal delay (GLO) :	-	-
• Antenna cable identification:	-	C123
Corresponding cable delay :	215 ns (entered (215+23) ns)	178.78 ns ± 0.4 ns
• UTC cable identification:	-	-
Corresponding cable delay :	-	-
Delay to local UTC :	-23 ns (entered 0 ns)	4.67 ns ± 0.13 ns
• Receiver trigger level:	0.5 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF
Latitude or X m	+3844066.36 m	+3844064.47 m
Longitude or Y m	+709657.18 m	+709657.61
Height or Z m	+5023125.00 m	+5023126.50 m

Antenna information

	Local:	Portable:
• Maker:	AOA	ITR TSA-2
• Type:	NIST-Type	GPS
• Serial number:		3-072002
If the antenna is temperature stabilised		
• Set temperature value :	-	-

Local antenna cable information

• Maker:	Air Dielectric Cables
• Type:	?
• Is it a phase stabilised cable:	no
• Length of cable outside the building :	about 30 m

General information

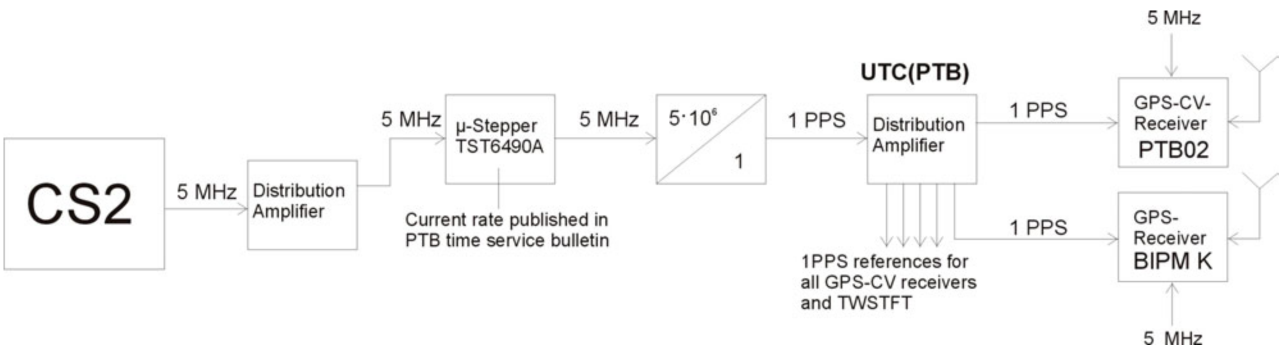
• Rise time of the local UTC pulse:	5 ns
• Is the laboratory air conditioned:	yes
• Set temperature value and uncertainty :	(23 ± 1) °C
• Set humidity value and uncertainty :	max. 50 % RF

Cable delay control

Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C123	178.78 ns ± 0.4 ns	179.6 ns ± 0.1 ns

Plot of the experiment set-up:

Link to the local UTC of both receivers and Antenna positions



Description of the local method of cable delay measurement:

1. Pulse method: Cable under test in Stop-Input of the Time-Interval-Counter.

BIPM GPS calibration information sheet

Laboratory:	BNM – SYRTE, Observatoire de Paris
Date and hour of the beginning of measurements:	7 July 2003
Date and hour of the end of measurements:	15 July 2003

Receiver setup information

	Local: NBS 51	**Portable: BIPM K**
• Maker:	Allen Osborne Associates	AOS
• Type:	TTR-5	TTS-2
• Serial number:	051	S/N 028
• Receiver internal delay (GPS) :	54 ns	0.0 (not calibrated)
• Receiver internal delay (GLO) :	-	-
• Antenna cable identification:	505 IF	C123
Corresponding cable delay :	168 ns ± 0.3 ns	178.78 ns ± 0.4 ns
• UTC cable identification:	503	497
Corresponding cable delay :	-	-
Delay to local UTC :	304 ns	306 ns
• Receiver trigger level:	0.5 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF
Latitude or X m	4 202 780.30 m	4 202 781.970 m
Longitude or Y m	171 370.03 m	171 364.125 m
Height or Z m	4 778 660.12 m	4 778 658.526 m

Antenna information

	Local:	**Portable:**
• Maker:	A.O.A.	ITR TSA-2
• Type:	-	GPS
• Serial number:	-	3-072002
If the antenna is temperature stabilised		
• Set temperature value :	-	-

Local antenna cable information

• Maker:	/
• Type:	RG-58
• Is it a phase stabilised cable:	No
• Length of cable outside the building :	Approximately 6 meters

General information

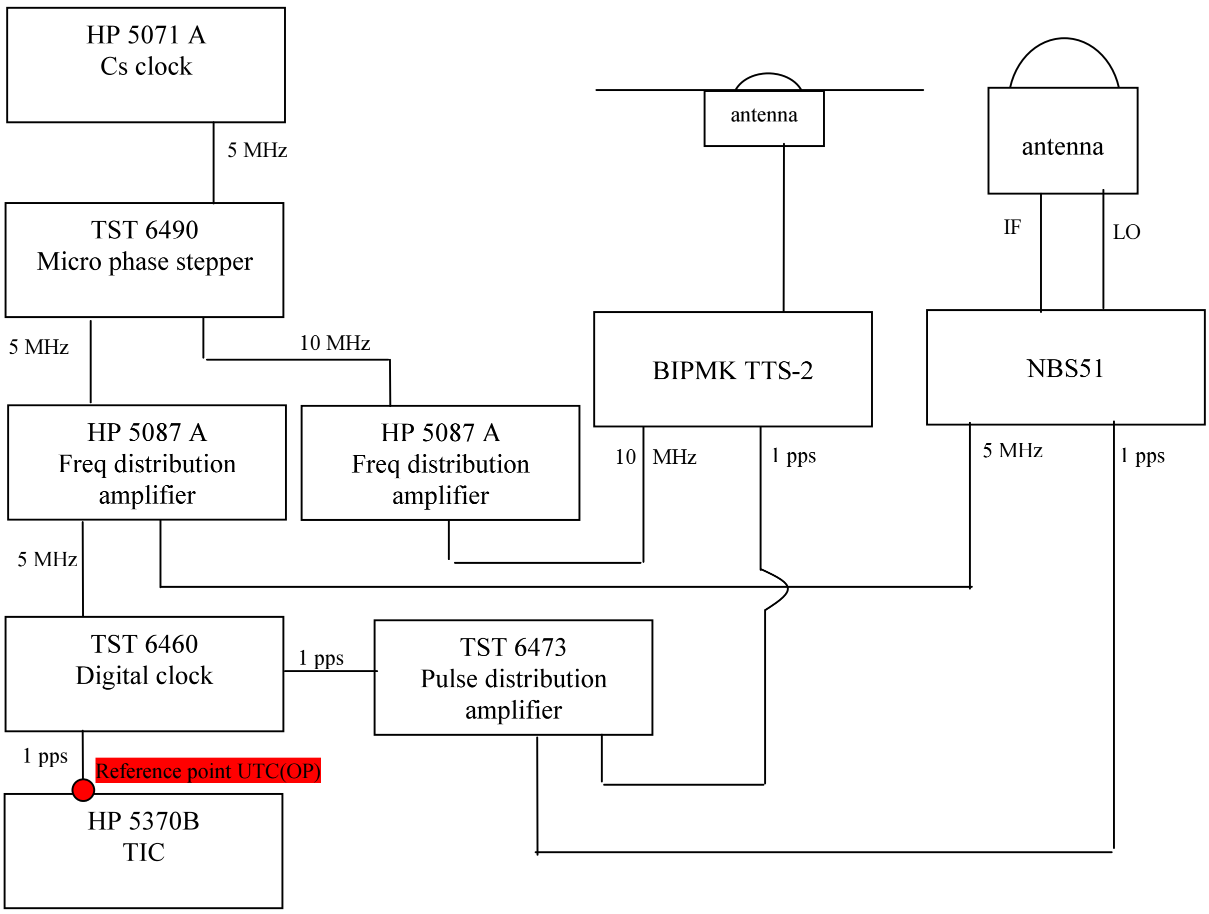
• Rise time of the local UTC pulse:	4 ns
• Is the laboratory air conditioned:	Yes
• Set temperature value and uncertainty :	(21.5 ± 2) °C
• Set humidity value and uncertainty :	/

Cable delay control

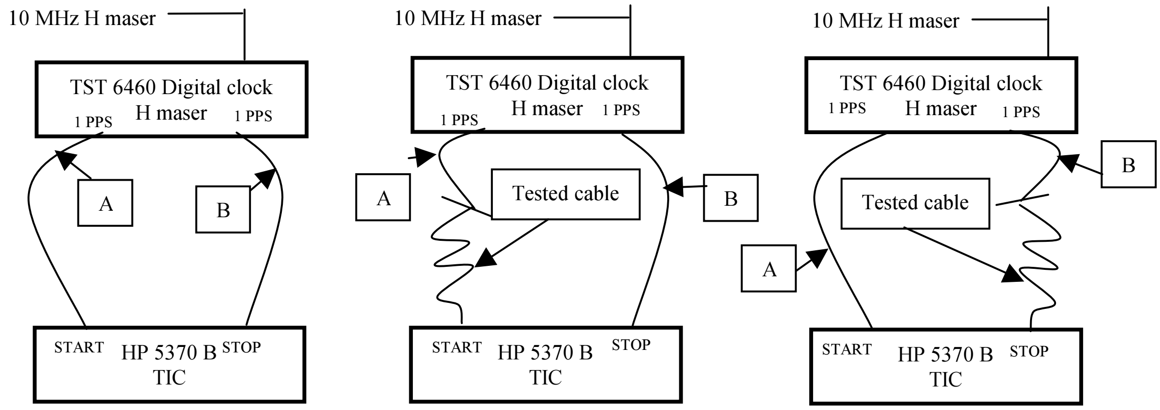
Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C123	178.78 ns ± 0.4 ns	179.9 ns ± 0.3 ns

Plot of the experiment set-up:

Link to the local UTC of both receivers and Antenna positions



Description of the local method of cable delay measurement:



Step 1, 3, 5 **Step 2** **Step 4**

The method used to calibrate the cables is a double wheight method in five steps as shown above.
At each step (i) the TIC gives the result (R_i)of 100 measurments.
The test cable delay is then obtained by the following formula:

$$\text{Delay} = \frac{R_2 - \left(\frac{R_1 + R_3}{2}\right) + \left(\frac{R_3 + R_5}{2}\right) - R_4}{2} + \text{corrections}$$

The corrections are the estimated delay introduced by adaptators : - 0.1 ns / adaptator

Appendix II

Measurement of portable cables at the visited laboratories

Laboratory	**BIPM C101 cable /ns**	**Measurement method**
BIPM	178.8 ± 0.4	Double Weight Pulse method
OP (before trip)	179.9 ± 0.3	Double Weight Pulse method
NPL		
IEN	181.0 ± 0.3	Pulse method
PTB	179.6 ± 0.1	Pulse method
VSL		
OP (after trip)	179.9 ± 0.3	Double Weight Pulse method

Appendix III

Daily averages of d$t_{k,i}$ for each laboratory *k*

LAB *k*	MJD	Mean offset /ns	Standard deviation of individual common view observations /ns	Standard deviation of the mean /ns	Number of individual common views
OP	52773	-7.26	2.22	0.50	20
	52774	-7.52	2.63	0.42	40
	52775	-7.16	2.85	0.43	44
	52776	-7.27	2.83	0.44	42
	52777	-6.89	2.30	0.33	44
	52778	-7.99	3.10	1.03	9
NPL	52780	-16.28	2.8	0.19	214
	52781	-15.97	2.13	0.14	219
IEN	52787	-5.86	2.38	0.17	192
	52788	-6.88	2.93	0.13	502
	52789	-7.94	2.39	0.11	506
	52790	-6.83	2.41	0.10	532
	52791	-7.87	2.54	0.11	543
	52792	-9.28	2.40	0.10	538
	52793	-7.28	2.18	0.18	143
PTB	52795	-10.96	3.98	0.87	21
	52796	-10.87	4.75	0.72	43
	52797	-11.14	4.77	0.73	43
	52798	-10.87	3.70	0.57	42
	52799	-10.39	3.73	0.56	44
VSL	52803	1.79	3.24	0.66	24
	52804	2.00	3.26	0.54	36
	52805	1.20	2.67	0.44	37
	52806	1.81	2.40	0.41	35
	52807	2.06	3.46	0.79	19
OP	52827	-3.57	4.07	0.85	23
	52828	-4.87	3.58	0.54	44
	52829	-5.30	3.54	0.53	45
	52830	-5.64	3.71	0.56	44
	52831	-5.80	3.30	0.49	45
	52832	-5.18	3.01	0.46	43
	52833	-4.66	2.97	0.46	42
	52834	-4.81	2.36	0.36	43
	52835	-5.05	3.62	0.77	22