Rapport BIPM-2008/01

BUREAU INTERNATIONAL DES POIDS ET MESURES

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

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Abstract

Following a suggestion made 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 GPS measurements which took place from 4 June 2004 to 27 July 2004, involving GPS and TWSTFT equipment located at the Observatoire de Paris (OP, Paris, France), the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany), the National Physical Laboratory (NPL, Teddington, United Kingdom) and the Van Swinden Laboratorium (VSL, Delft, the Netherlands). The GPS receiver travelled with the TWSTFT portable station.

INTRODUCTION

Following a suggestion made 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]. Exercise described here serves as an independent check of the TWSTFT calibration [4].

As for previous trips 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. The OP has often served in the past as reference laboratory for GPS calibrations. Over the last twenty years its 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; and
- serve as a independent check of the TWSTFT calibration or as a provisional differential calibrations of the two-way equipment at the laboratories.

This report details an exercise which took place from 4 June 2004 to 27 July 2004. Succeeding visits are scheduled to take place at four to five month intervals.

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	051
PTB	AOS	TTS-2	-
NPL	TFS	TFS receiver	TSF101
VSL	3S Navigation	R-100/40T	0018
BIPM portable receiver	AOS	TTS-2	036

The portable BIPM receiver is equipped with a C128 cable. Its delay measured at the BIPM is 187.75 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 very beginning of the linear part of the rising pulse at each end of the cable using a 0.5 V trigger level [5].

The delay of this cable was also measured at the visited laboratories. 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 dt_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.

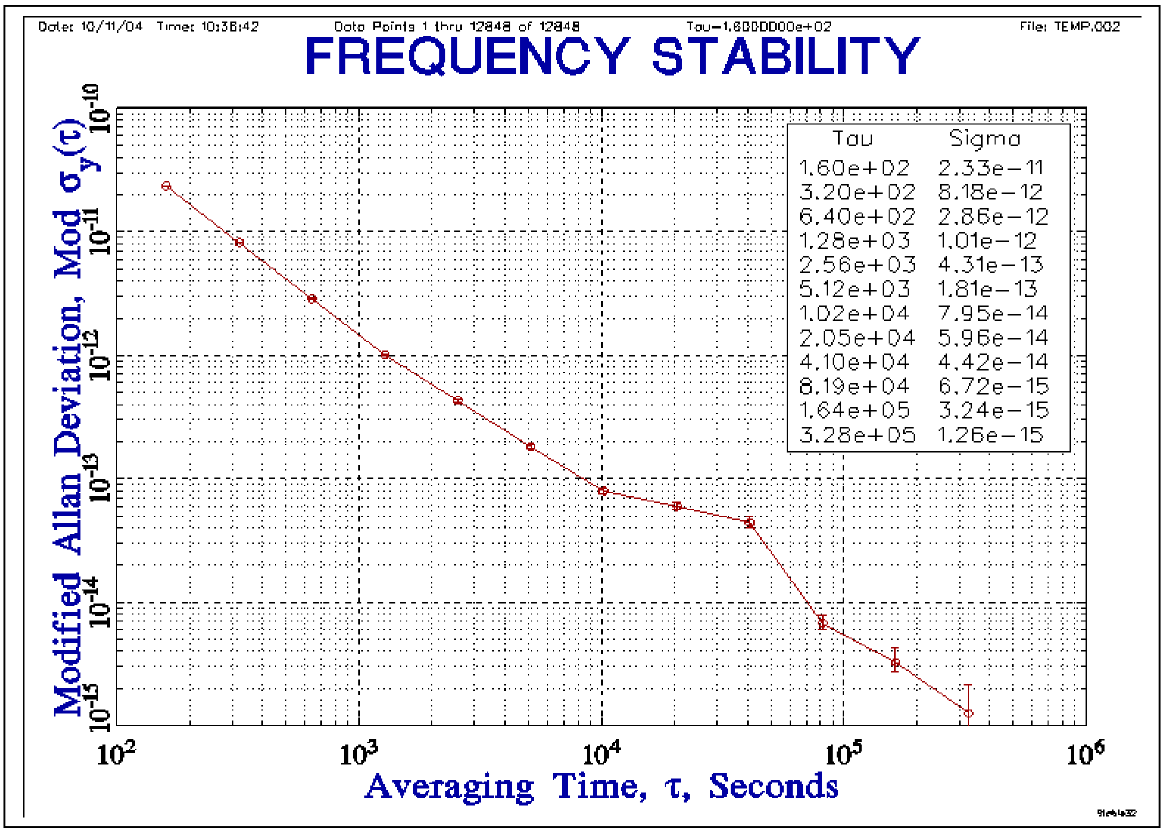

Figure 1. Square root of the modified Allan variance of the time series dt_{PTB} for the period: 14 June 2004 to 7 July 2004.

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.

[REF(Lab*k*)-(GPS TIME)] $_{\text{BIPM}}$ **-[REF(Lab*k*)-(GPS TIME)]** $_{\text{Lab}k}$

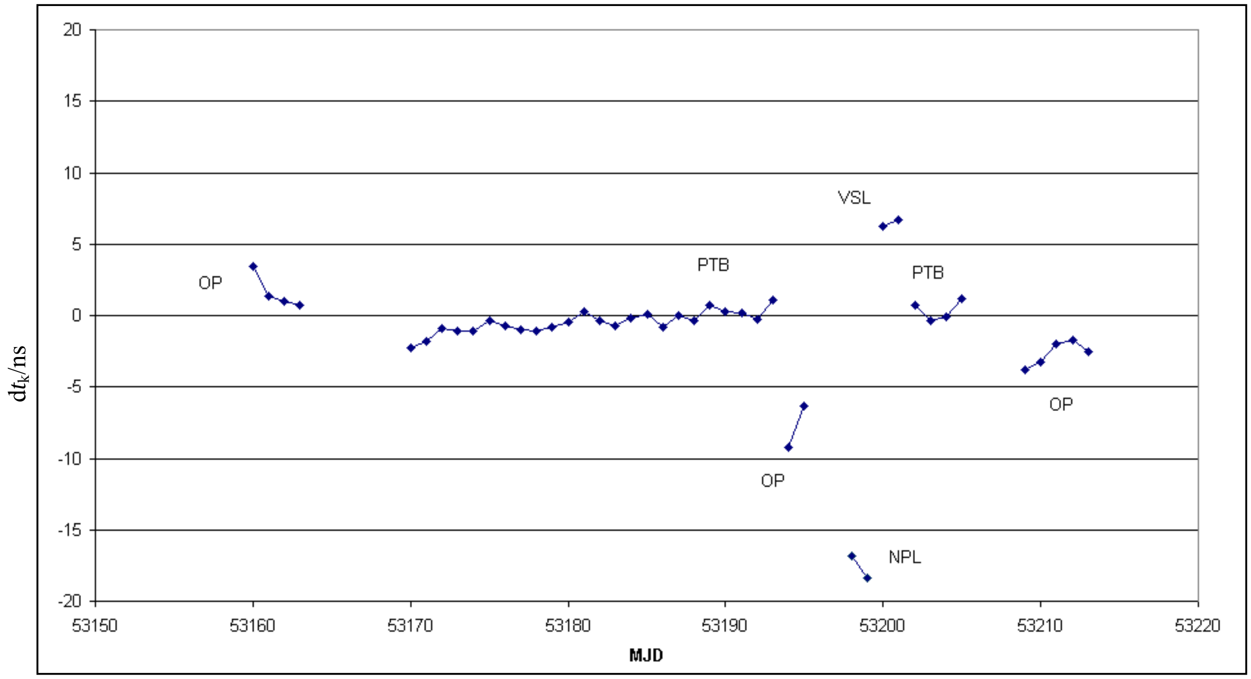

Figure 2. Daily averages of $dt_{k,i}$ for each laboratory *k* (see Appendix III).

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 2004	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	04/06 - 07/06	138	1.34	3.03	0.7	1.21
PTB	14/06 - 07/07	12847	-0.49	2.52	0.2	0.75
OP	08/07 - 09/07	43	-7.52	2.75	0.4	2.06
NPL	12/07 - 13/07	455	-17.34	4.12	0.2	1.07
VSL	14/07 - 15/07	307	6.53	8.20	0.6	0.36
PTB	16/07 - 19/07	1527	0.05	3.07	1.5	0.71
OP	23/07 - 27/07	173	-2.49	3.24	0.5	0.88

The "closure" – the difference between the first and last sets of measurements made at the OP – was within a few nanoseconds, which is within acceptable limits. Also, after averaging the results of the two sets of measurements at the OP, we 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*(PTB)-*UTC*(OP)]	+0.1	3.0
[*UTC*(NPL)-*UTC*(OP)]	-16.8	3.0
[*UTC*(VSL)-*UTC*(OP)]	+7.1	8.0
[*UTC*(PTB)-*UTC*(OP)]	+0.6	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.

For information we provide in Table 4 results of some past calibrations between NIST and OP.

Table 4. Some past calibrations between NIST and OP: *d* are differential time corrections to be added to [*UTC*(NIST)-*UTC*(OP)], and *u(d)* are estimated uncertainties for the periods of comparisons.

Date	*d*/ns	*u(d)*/ns	Reference
July 1983	0.0	2.0	[6]
January 1985	–7.0#	13.0	[7]
September 1986	0.7*	2.0	[8]
October 1986	–1.4*	2.0	[8]
January 1988	–3.8*	3.0	[9]
April 1988	0.6*	3.0	[10]
March 1995	–3.7*	1.0	[11]
May 1996	–0.7*	1.5	[12]
May 2002	–5.0*	3.0	[13]
July 2003	–5.6*	1.9	[14]
December 2003	-4.6*	3.0	[15]

NBS03 receiver at NIST
* NBS10 receiver at NIST

CONCLUSION

The BIPM is conducting a series of differential calibrations of GPS equipment located in UTC time laboratories equipped with two-way stations [2, 3]. Exercise described here serves as an independent check of the TWSTFT calibration [4].

The present measurements were performed under good conditions with a closure of GPS travelling equipment at the OP within a few nanoseconds, which is within acceptable limits. The GPS time equipment of PTB agrees within one nanosecond with reference equipment at the OP. At the NPL, the offset is large but this was already known.
At the VSL, the reference GPS receiver VSL01was unavailable and a back-up R-100/40T was used, exhibiting a large measurement noise.

Acknowledgements

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

REFERENCES

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[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.
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[12] M.A. Weiss, "Calibration of OP Receiver AOA51 Against NIST Receiver NBS10" March 1996.
[13] W. Lewandowski, P. Moussay, "Determination of the differential time corrections For GPS time equipment located at the OP, IEN, ROA, PTB, NIST, and USNO", *BIPM Report -2002/02*, July 2002.
[14] M.A. Weiss, "Calibration of OP Receiver AOA51 Against NIST Receiver NBS10" July 2003.
[15] W. Lewandowski, L. Tisserand, "Determination of the differential time corrections for GPS time equipment located at the OP, PTB, AOS, KRISS, CRL, NIST, USNO and APL", *BIPM Report -2004/06*.

<u>Appendix I</u>

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:	4 June 2004 (53160)
Date and hour of the end of measurements:	7 June 2004 (53163)

Receiver setup information

	Local: NBS51	**Portable: BP0N**
• Maker:	Allen Osborne Associates	BIPM
• Type:	TTR-5	TTS-2
• Serial number:	051	S/N 036
• Receiver internal delay (GPS) :	54 ns	8.0
• Receiver internal delay (GLO) :	-	-
• Antenna cable identification:	505 IF	C128
Corresponding cable delay :	168 ns +/- 0,3 ns	187.75 ns ± 0.4 ns
• 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	4 202 783.64 m
Longitude or Y m	171 370.03 m	171 367.43 m
Height or Z m	4 778 660.12 m	4 778 657.39 m

Antenna information

	Local:	**Portable:**
• Maker:	Allen Osborne Associates	Motorola
• Type:	-	GPS
• Serial number:	-	AN16N00210
If the antenna is temperature stabilised		
• Set temperature value :	-	60 °C

Local antenna cable information

• Maker:	-
• Type:	RG-58
• Is it a phase stabilised cable:	No
• Length of cable outside the building :	Approximately 20 meters

General information

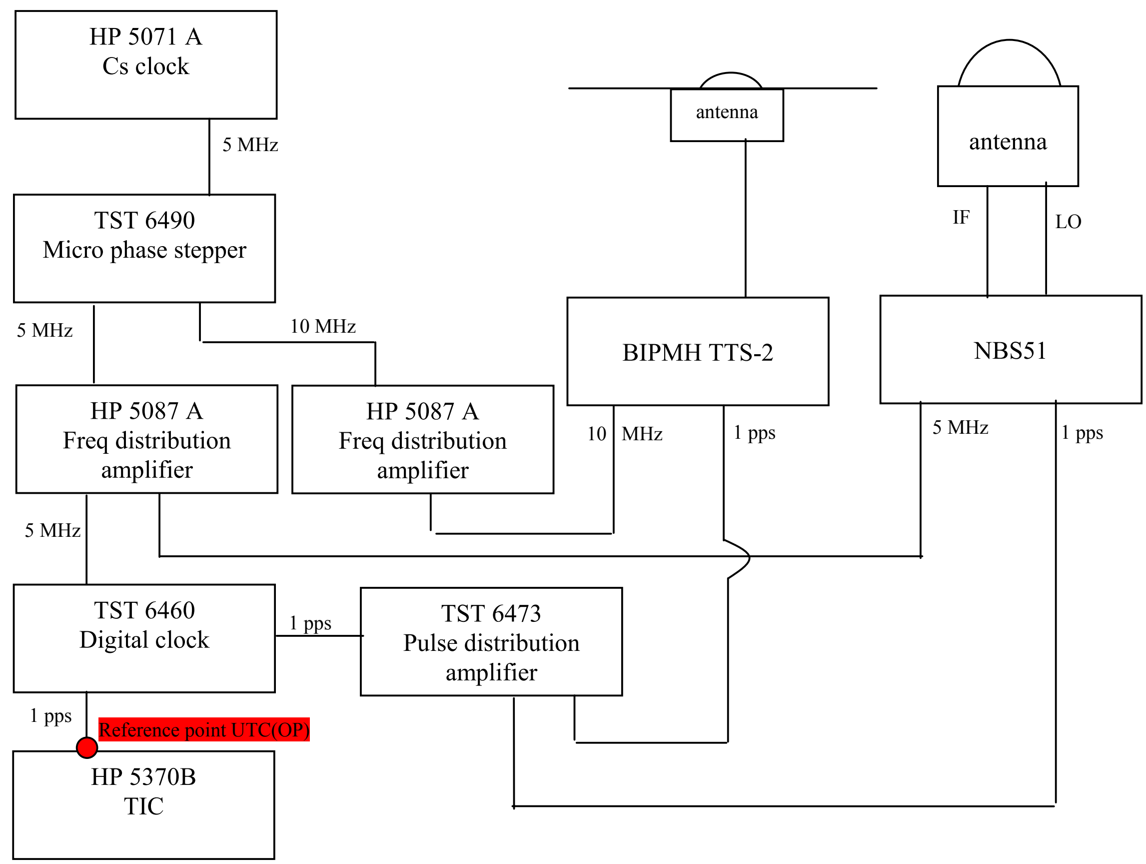
• Rise time of the local UTC pulse:	4 ns
• Is the laboratory air conditioned:	Yes
• Set temperature value and uncertainty :	(21.5 +/- 2) °C
• Set humidity value and uncertainty :	-

Cable delay control

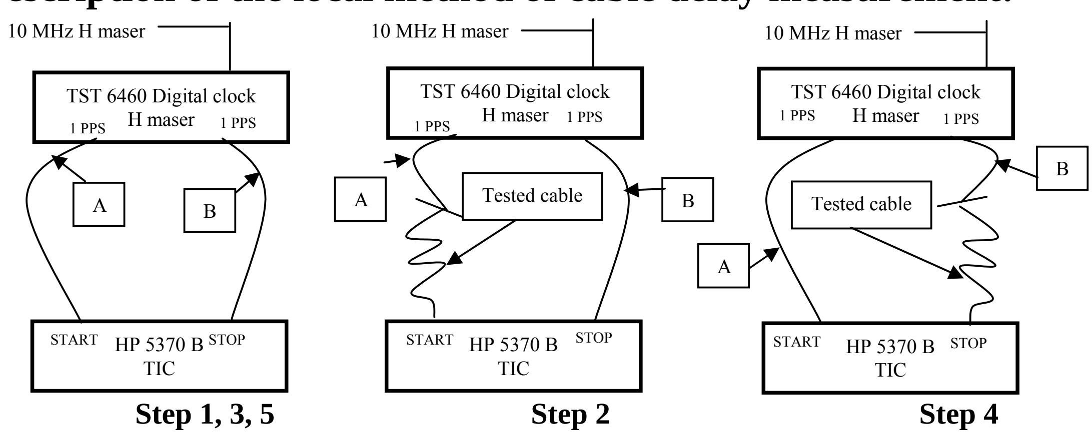
Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C128	187.75 ns ± 0.4 ns	-

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 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

BIPM GPS calibration information sheet

Laboratory:	PTB
Date and hour of the beginning of measurements:	2004-06-14 12:00 UTC
Date and hour of the end of measurements:	2004-07-07 06:00 UTC

Receiver setup information

	Local:	Portable: BP0N
• Maker:	AOS	BIPM
• Type:	TTS-2	TTS-2
• Serial number:	-	S/N 036
• Receiver internal delay (GPS) :	17.2 ns	8.0
• Receiver internal delay (GLO) :	-	-
• Antenna cable identification:	-	C128
Corresponding cable delay :	245.6 ns	187.75 ns ± 0.4 ns
• Delay to local UTC :	35.3 ns	UTCPTB-REF=50.16±0.03ns
• Receiver trigger level:	0.5 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF “mast P5”
Latitude or X m	3844062.69 m	3844063.47 m
Longitude or Y m	709659.24 m	709657.99 m
Height or Z m	5023127.69 m	5023127.24 m

Antenna information

	Local:	Portable:
• Maker:	-	Motorola
• Type:	active micro strip patch ant.	GPS
• Serial number:	-	AN16N00210
If the antenna is temperature stabilised		
• Set temperature value :	-	60 °C

Local antenna cable information

• Maker:	-
• Type:	single coaxial cable (6 dB loss at 1575.42 MHz)
• Is it a phase stabilised cable:	no
• Length of cable outside the building :	appr. 30 m

General information

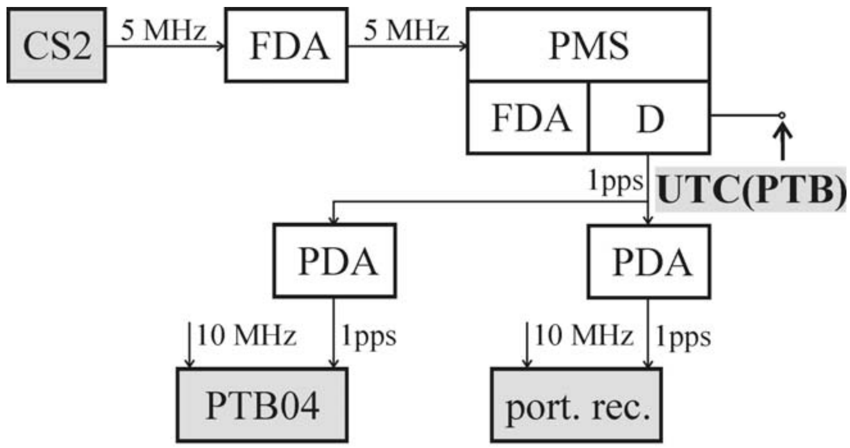
• Rise time of the local UTC pulse:	5 ns
• Is the laboratory air conditioned:	yes
• Set temperature value and uncertainty :	(23 ± 1) °C
• Set humidity value and uncertainty :	max. 50 %

Cable delay control

Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C128	187.75 ns ± 0.4 ns	187.76 ns ± 0.1 ns

Plot of the experiment set-up:

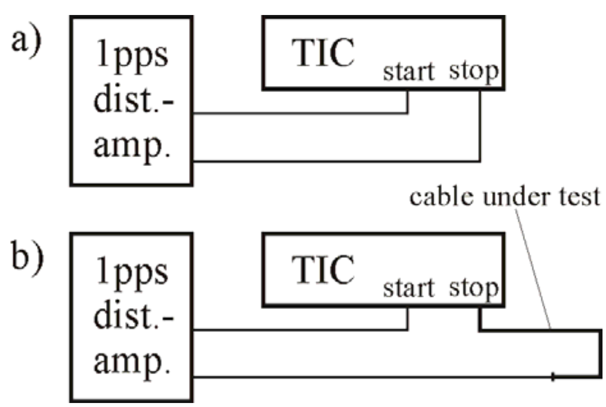
Link to the local UTC of both receivers and Antenna positions



FDA frequency distribution amplifier
PMS phase micro stepper
PDA pulse distrubution amplifier
D divider

Description of the local method of cable delay measurement:

The cable delay was determined by subtracting measurement a) from b).
TIC: SR620, Trigger-Level: 0.5 V



BIPM GPS calibration information sheet

Laboratory:	BNM-SYRTE (Observatoire de Paris)
Date and hour of the beginning of measurements:	8 July 2004 (53194)
Date and hour of the end of measurements:	9 July 2004 (53195)

Receiver setup information

	Local: NBS51	**Portable: BP0N**
• Maker:	Allen Osborne Associates	BIPM
• Type:	TTR-5	TTS-2
• Serial number:	051	S/N 036
• Receiver internal delay (GPS) :	54 ns	8.0
• Receiver internal delay (GLO) :	-	-
• Antenna cable identification:	505 IF	C128
Corresponding cable delay :	168 ns +/- 0,3 ns	187.75 ns ± 0.4 ns
• 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	4 202 783.64 m
Longitude or Y m	171 370.03 m	171 367.43 m
Height or Z m	4 778 660.12 m	4 778 657.39 m

Antenna information

	Local:	**Portable:**
• Maker:	Allen Osborne Associates	Motorola
• Type:	-	GPS
• Serial number:	-	AN16N00210
If the antenna is temperature stabilised		
• Set temperature value :	-	60 °C

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

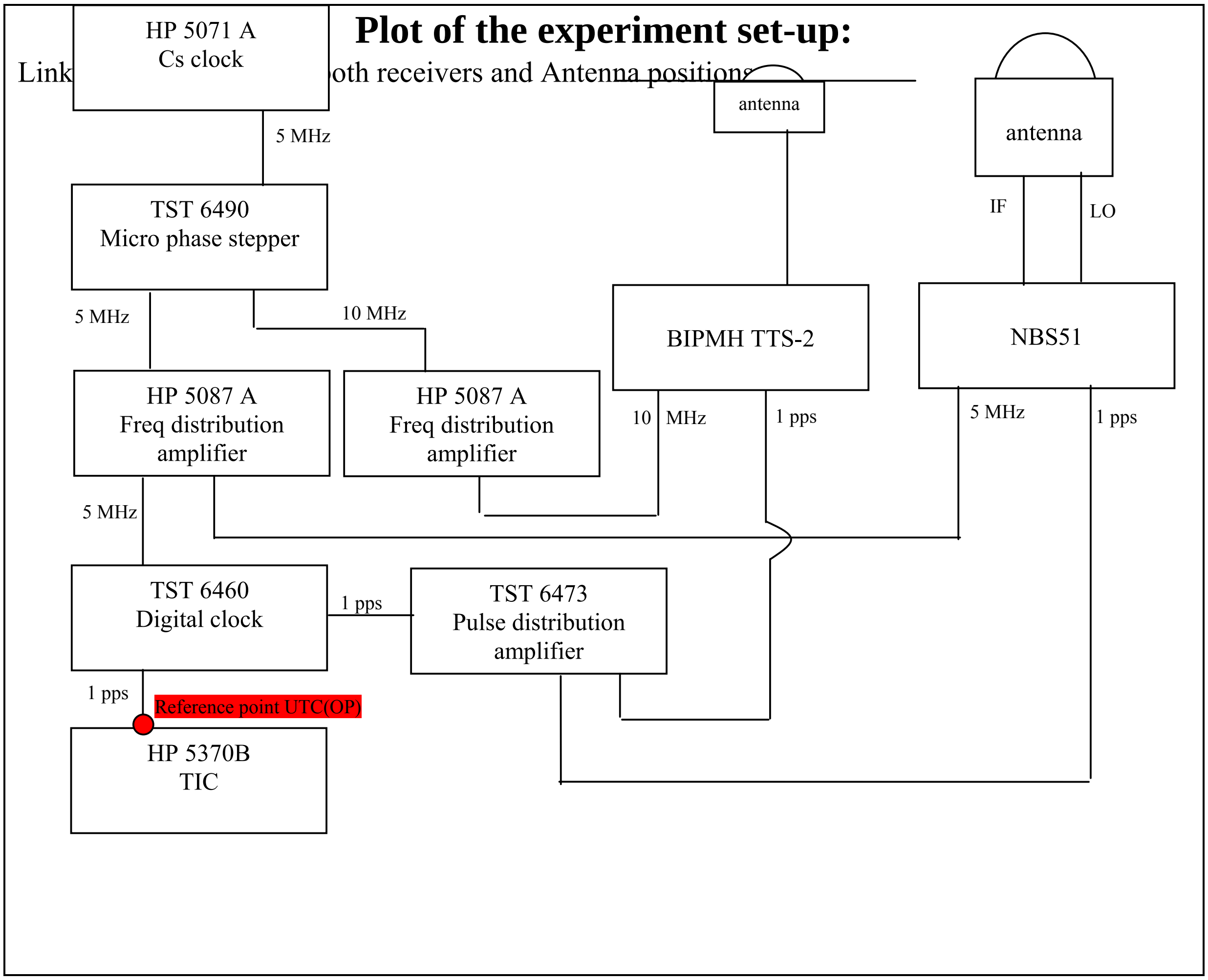
• Rise time of the local UTC pulse:	4 ns
• Is the laboratory air conditioned:	Yes
• Set temperature value and uncertainty :	(21.5 +/- 2) °C
• Set humidity value and uncertainty :	-

Cable delay control

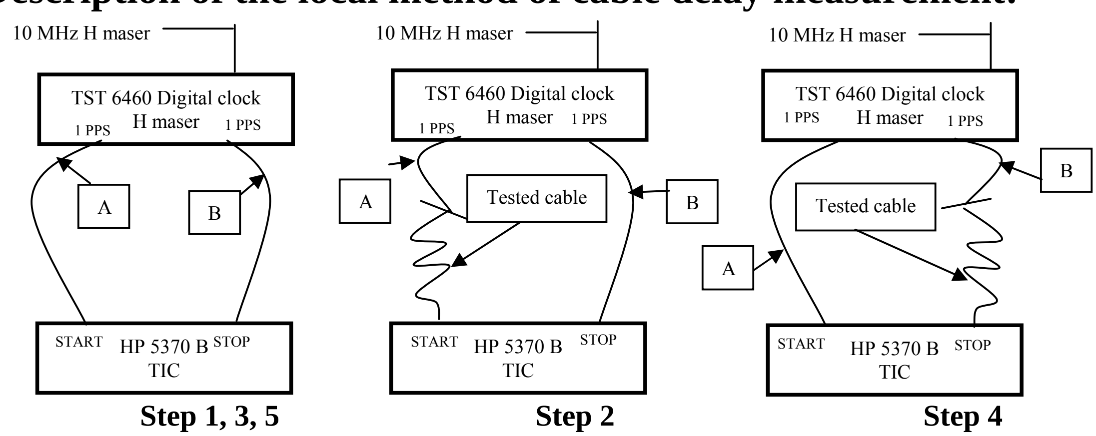
Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C128	187.75 ns ± 0.4 ns	-

Plot of the experiment set-up:

Link … oth 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 measurments.
The test cable delay is then obtained by the following formula:

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

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

BIPM GPS calibration information sheet

Laboratory:	VSL
Date and hour of the beginning of measurements:	MJD 53200 18:00:00 UTC
Date and hour of the end of measurements:	MJD 53201 08:00:00 UTC

Receiver setup information

	Local: 3SN	Portable: BP0N
• Maker:	3 S Navigation	EMDE Electronics
• Type:	R-100/40T	TTS-2
• Serial number:	RF #0018	S/N 036
• Receiver internal delay (GPS) :	254 ns	8.0
• Receiver internal delay (GLO) :	27 ns	-
• Antenna cable identification:	GLO #1	C128
Corresponding cable delay :	621 ns	187.75 ns ± 0.4 ns
• Delay to local UTC :	24.3 ns	
• Receiver trigger level:	0.5 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF
Latitude or X m	+3923530.80 m	+3923530.61 m
Longitude or Y m	+300595.90 m	+300596.76 m
Height or Z m	+5002840.97 m	+5002841.06 m

Antenna information

	Local:	Portable:
• Maker:	3S Navigation	Motorola
• Type:	TSA 100	GPS
• Serial number:		AN16N00210
If the antenna is temperature stabilised		
• Set temperature value :	37°C	60 °C

Local antenna cable information

• Maker:	
• Type:	RG 214 u
• Is it a phase stabilised cable:	no
• Length of cable outside the building :	5 m

General information

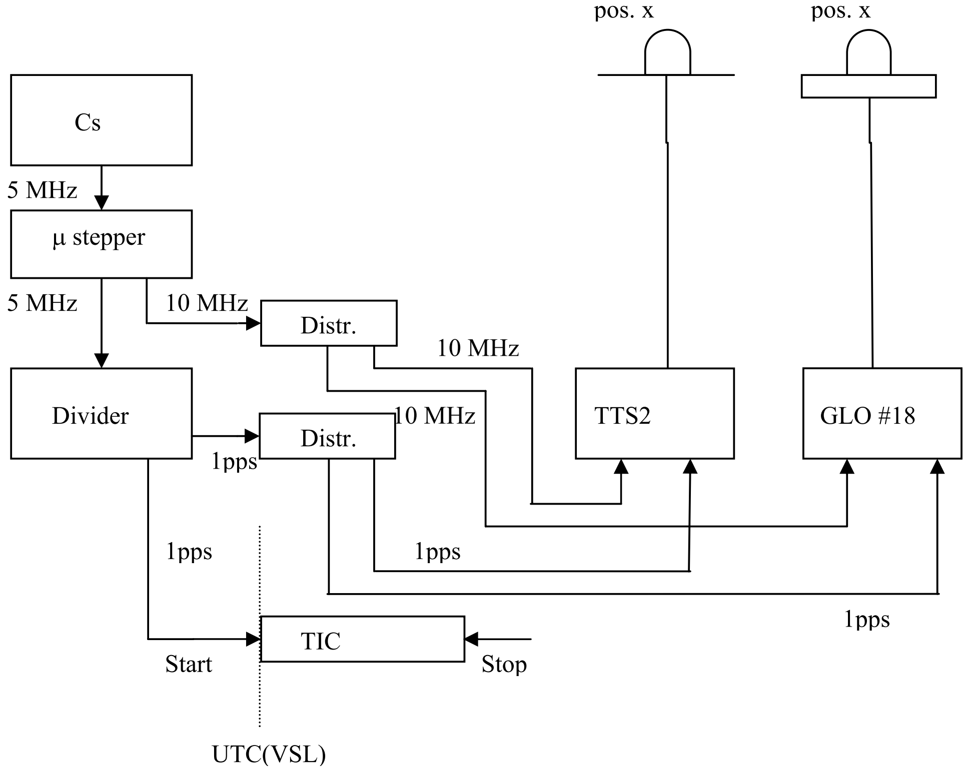
• Rise time of the local UTC pulse:	5 ns
• Is the laboratory air conditioned:	yes
• Set temperature value and uncertainty :	23°C ±0.5°C
• Set humidity value and uncertainty :	45% ±5% RH

Cable delay control

Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C101	187.75 ns ± 0.4 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:

BIPM GPS calibration information sheet

Laboratory:	PTB
Date and hour of the beginning of measurements:	2004-07-16 14:00 UTC
Date and hour of the end of measurements:	2004-07-19 06:45 UTC

Receiver setup information

	Local:	Portable: BP0N
• Maker:	AOS	BIPM
• Type:	TTS-2	TTS-2
• Serial number:	-	S/N 036
• Receiver internal delay (GPS) :	17.2 ns	8.0
• Receiver internal delay (GLO) :	-	-
• Antenna cable identification:	-	C128
Corresponding cable delay :	245.6 ns	187.75 ns ± 0. ns
• Delay to local UTC :	35.3 ns	UTCPTB-REF=50.16±0.03ns*
• Receiver trigger level:	0.5 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF “mast P5”
Latitude or X m	3844062.69 m	3844063.47 m
Longitude or Y m	709659.24 m	709657.99 m
Height or Z m	5023127.69 m	5023127.24 m

Antenna information

	Local:	Portable:
• Maker:	-	Motorola
• Type:	active micro strip patch ant.	GPS
• Serial number:	-	AN16N00210
If the antenna is temperature stabilised		
• Set temperature value :	-	60 °C

Local antenna cable information

• Maker:	-
• Type:	single coaxial cable (6 dB loss at 1575.42 MHz)
• Is it a phase stabilised cable:	no
• Length of cable outside the building :	appr. 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 %

Cable delay control

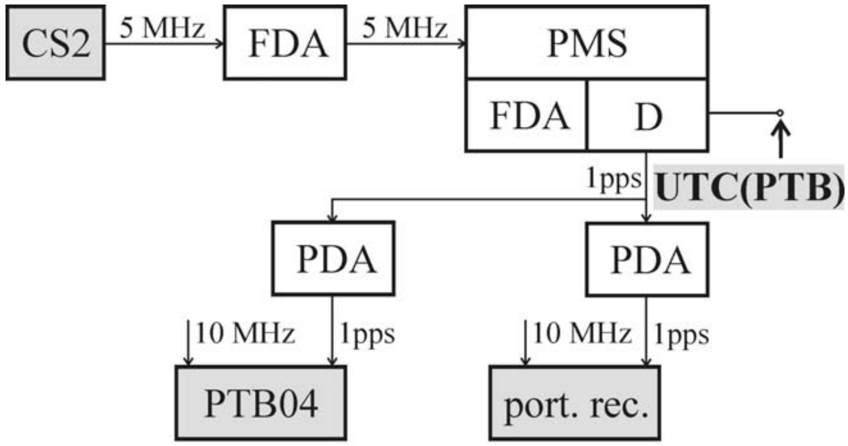
Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C128	187.5 ns ± 0. ns	187.6 ns ± 0. ns **

* UTCPTB-REF=50.13±0.01ns (2004-07-16) confirmed the value determined during 1st visit.

** Delay measurement by local method was not repeated during 2nd calibration exercise.

Plot of the experiment set-up:

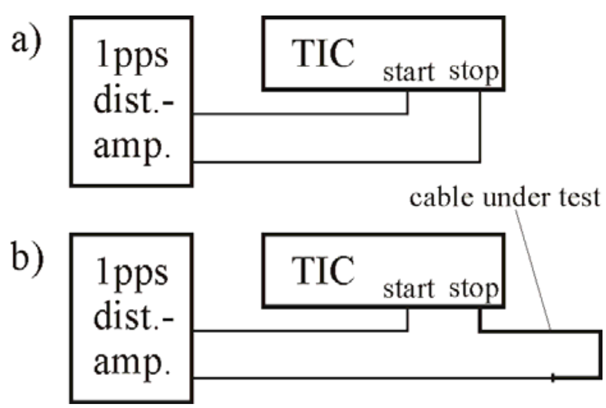
Link to the local UTC of both receivers and Antenna positions



FDA frequency distribution amplifier
PMS phase micro stepper
PDA pulse distrubution amplifier
D divider

Description of the local method of cable delay measurement:

The cable delay was determined by subtracting measurement a) from b).
TIC: SR620, Trigger-Level: 0.5 V



Appendix II

Measurement of portable cables at the visited laboratories

Laboratory	BIPM C128 cable /ns	Measurement method
BIPM	187.75 ± 0.4	Double Weight Pulse method
OP	-	-
PTB	187.76 ± 0.1	Pulse method
NPL	-	-
VSL	-	-

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	53160	3.42	2.36	0.59	16
	53161	1.38	2.96	0.43	47
	53162	1.04	3.35	0.49	47
	53163	0.74	2.51	0.47	29
PTB	53170	-2.28	2.44	0.15	282
	53171	-1.81	2.53	0.11	555
	53172	-0.88	2.55	0.11	565
	53173	-1.10	2.55	0.11	563
	53174	-1.07	2.41	0.10	536
	53175	-0.34	2.44	0.10	568
	53176	-0.73	2.77	0.12	554
	53177	-1.00	2.76	0.12	573
	53178	-1.06	2.71	0.11	571
	53179	-0.82	2.25	0.09	567
	53180	-0.45	2.07	0.09	554
	53181	0.29	1.98	0.08	553
	53182	-0.35	2.36	0.10	569
	53183	-0.68	2.57	0.11	573
	53184	-0.19	2.16	0.09	554
	53185	0.11	2.24	0.09	560
	53186	-0.77	2.54	0.11	584
	53187	0.00	2.49	0.10	580
	53188	-0.40	2.44	0.10	559
	53189	0.68	2.15	0.09	568
	53190	0.28	2.33	0.10	570
	53191	0.21	2.45	0.10	577
	53192	-0.26	2.65	0.11	573
	53193	1.11	2.23	0.19	140
OP	53194	-9.21	2.24	0.56	16
	53195	-6.29	2.80	0.53	28
NPL	53198	-16.86	4.23	0.24	308
	53199	-18.37	3.66	0.30	148
VSL	53200	6.22	7.87	0.67	137
	53201	6.73	8.47	0.65	171
PTB	53202	0.75	2.70	0.18	219
	53203	-0.39	3.30	0.14	575
	53204	-0.08	2.95	0.12	572
	53205	1.14	2.64	0.21	162
OP	53209	-3.80	2.98	0.65	21
	53210	-3.27	2.99	0.44	46
	53211	-2.00	2.60	0.39	44
	53212	-1.68	3.94	0.59	45
	53213	-2.51	3.27	0.77	18