Rapport BIPM-2010/03

BUREAU INTERNATIONAL DES POIDS ET MESURES

Relative characterization of GPS time equipment delays at the OP, PTB, AOS, USNO and IT

W. Lewandowski and L. Tisserand

2010

Pavillon de Breteuil, F-92312 SEVRES Cedex

Abstract

The BIPM continues a series of differential calibrations of GPS equipment located in time laboratories contributing to TAI. This report details measurements that took place from 1 September 2006 to 16 June 2008, involving GPS time equipment located at the Observatoire de Paris (OP, Paris, France), the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany), the Astrogeodynamical Observatory Space Research Centre P.A.S. (AOS, Borowiec, Poland), the U.S. Naval Observatory (USNO, Washington D.C., USA) and the Istituto Nazionale di Ricerca Metrologica (INRIM, Turin, Italy).

INTRODUCTION

The BIPM is conducting a series of differential calibrations of GPS equipment located in time laboratories contributing to TAI. This report details an exercise that took place from 1 September 2006 to 16 June 2008.

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 often served in the past as the 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 provisional differential calibrations of the two-way equipment at the laboratories.

EQUIPMENT

Details of the GPS receivers 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
OP	AOA	TTR-6	287
PTB	AOS	TTS-3	014
AOS	AOS	TTS-2	023
USNO	AOS	TTS-2	014
IT	AOS	TTS-3	022
BIPM portable receiver	AOS	TTS-3	012

The BIPM portable receiver is equipped with a C128 cable. Its delay measured at the BIPM was 136.2 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 [1].

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 $\mathrm{d}t_k$ is then analysed, for each of the laboratories visited, using 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.

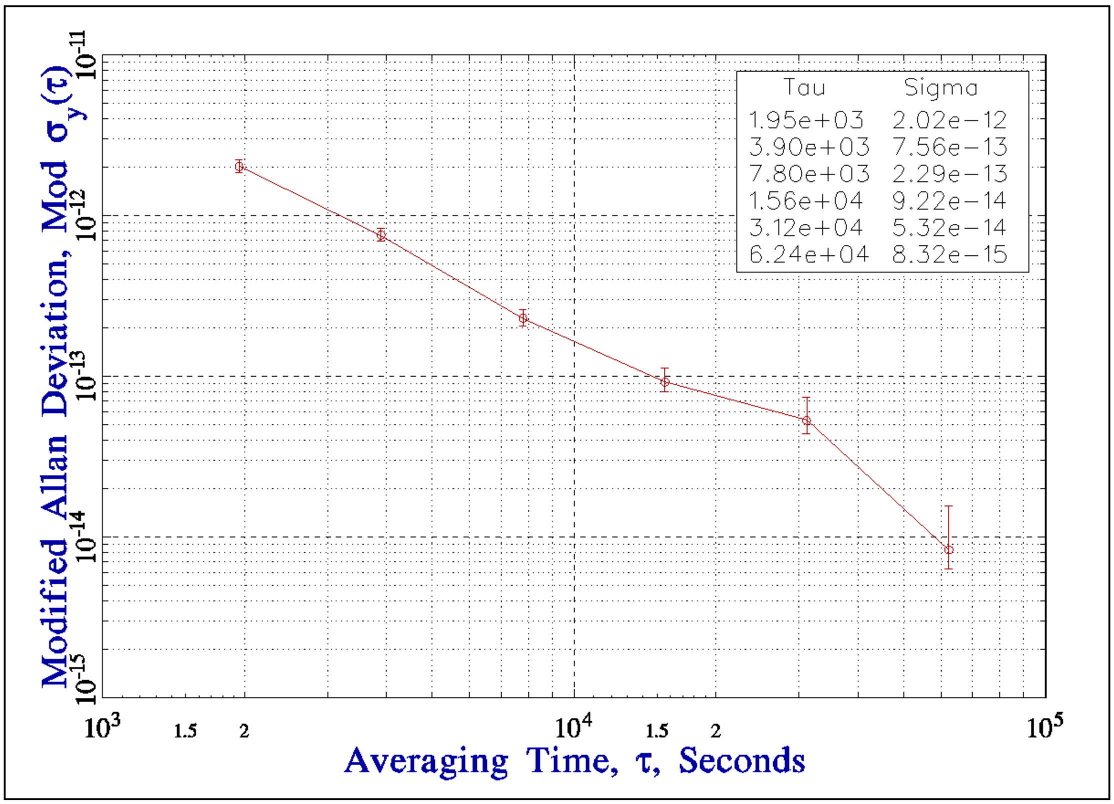


Figure 1. Square root of the modified Allan variance of the time series $\mathrm{d}t_{\mathrm{OP}}$ for the period: 1-4 September 2006.

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

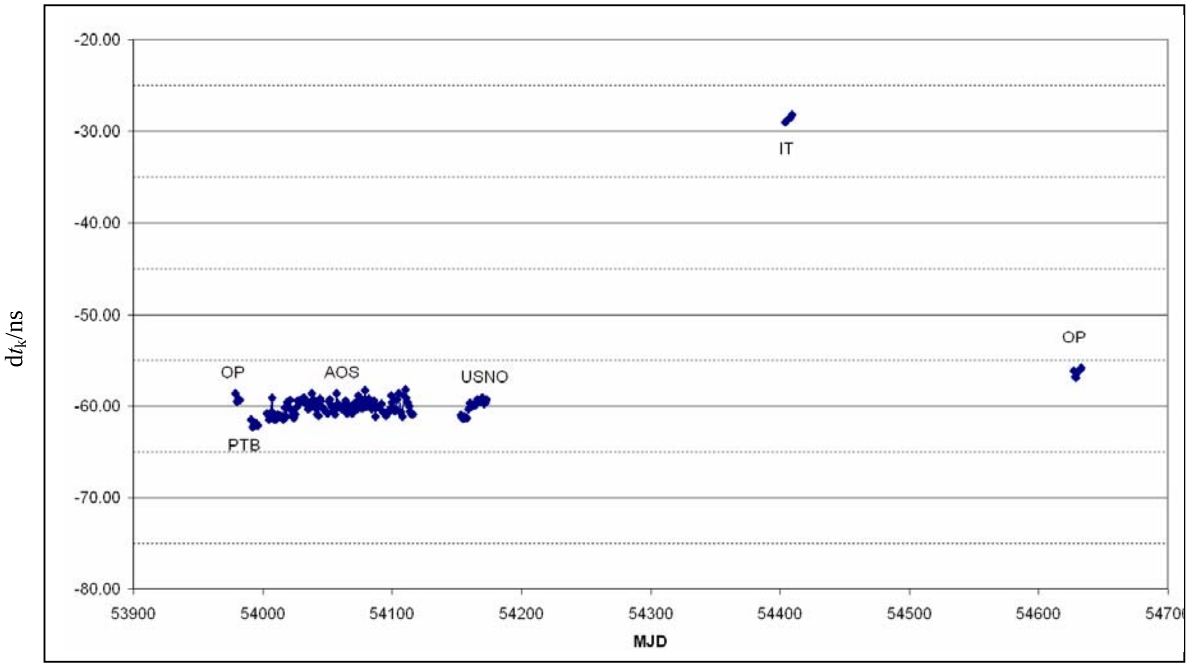


Figure 2. Daily averages of $dt_{k,i}$ for each laboratory k (see Appendix III).

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	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	1/09/06 - 4/09/06	133	–59.25	2.34	0.5	0.39
PTB	13/09/06 - 18/09/06	3051	–61.98	1.62	0.3	0.29
AOS	25/09/06 - 16/01/07	60914	–60.14	1.54	0.4	0.75
USNO	22/02/07 - 14/03/07	11304	–60.10	1.67	0.3	0.81
IT	31/10/07 - 5/11/07	3296	–28.64	2.92	0.4	0.29
OP	10/06/08 - 16/06/08	272	–56.40	1.86	0.4	0.40

The "closure" – the difference between the first and last sets of measurements made at the OP – was within a few nanoseconds, which is an excellent result. 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*(PTB)-*UTC*(OP)]	–4.2	3.0
[*UTC*(AOS)-*UTC*(OP)]	–2.3	3.0
[*UTC*(USNO)-*UTC*(OP)]	–2.3	3.0
[*UTC*(IT)-*UTC*(OP)]	–29.2	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 of Rapport BIPM-2010/3 results of some past calibrations between NIST and OP.

CONCLUSION

These measurements are part of a series of differential calibrations of GPS equipment located in time laboratories contributing to TAI. They improve the accuracy of access to UTC for the participating laboratories.

The present measurements were performed under good conditions with excellent closure of the travelling equipment at the OP. The GPS time equipment of most of the participating laboratories agrees within a few nanoseconds with the reference equipment at the OP. At the INRIM the offset is large and required an appropriate correction.

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

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

[2] D. Allan, D. Davis, M.A. Weiss, Personal communication, 1983.

[3] J. Buisson, Personal communication, 1985.

[4] W. Lewandowski, M. A. Weiss, "A Calibration of GPS Equipment at Time and Frequency Standards Laboratories in the USA and Europe", *Metrologia,* **24**, pp. 181-186, 1987.

[5] BIPM Calibration Certificate of 19 January 1988.

[6] BIPM Letter of 15 June 1988, BG/9G.69.

[7] M.A. Weiss, "Calibration of OP Receiver AOA51 Against NIST Receiver NBS10" March 1995.

[8] M.A. Weiss, "Calibration of OP Receiver AOA51 Against NIST Receiver NBS10" March 1996.

Appendix I

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

BIPM calibration information sheet

Laboratory:	PTB
Date and hour of the beginning of measurements:	2006-09-13 06:00 UTC
Date and hour of the end of measurements:	2006-09-19 12:00 UTC

Receiver setup information

	Local:	**Portable: BP0Q**
• Maker:	AOS	AOS
• Type:	TTS-3	TTS-3
• Serial number:	014	012
• Receiver internal delay (GPS) :	-29.2 ns	30.5
• Receiver internal delay (GLO) :	-29.2 ns	0.0
• Antenna cable identification:	-	C130
Corresponding cable delay :	195.0 ns	136.2 ns ± 0.4 ns
• Delay to local UTC :	47.9 ns	51.0 ns ± 0.5 ns
• Receiver trigger level:	0.5 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF
Latitude or X m	+3844057.34 (PTB mast P12)	+3844056.75 (PTB mast P13)
Longitude or Y m	+709663.63	+709664.09
Height or Z m	+5023131.42	+5023131.73

Antenna information

	Local:	**Portable:**
• Maker:	Javad	Javad
• Type:	MarAnt+	MarAnt+
• Serial number:	MA+#1718	1713
If the antenna is temperature stabilised		
• Set temperature value :	-	-

Local antenna cable information

• Maker:	-
• Type:	-
• Is it a phase stabilised cable:	no
• Length of cable outside the building :	Approx. 30 m

General information

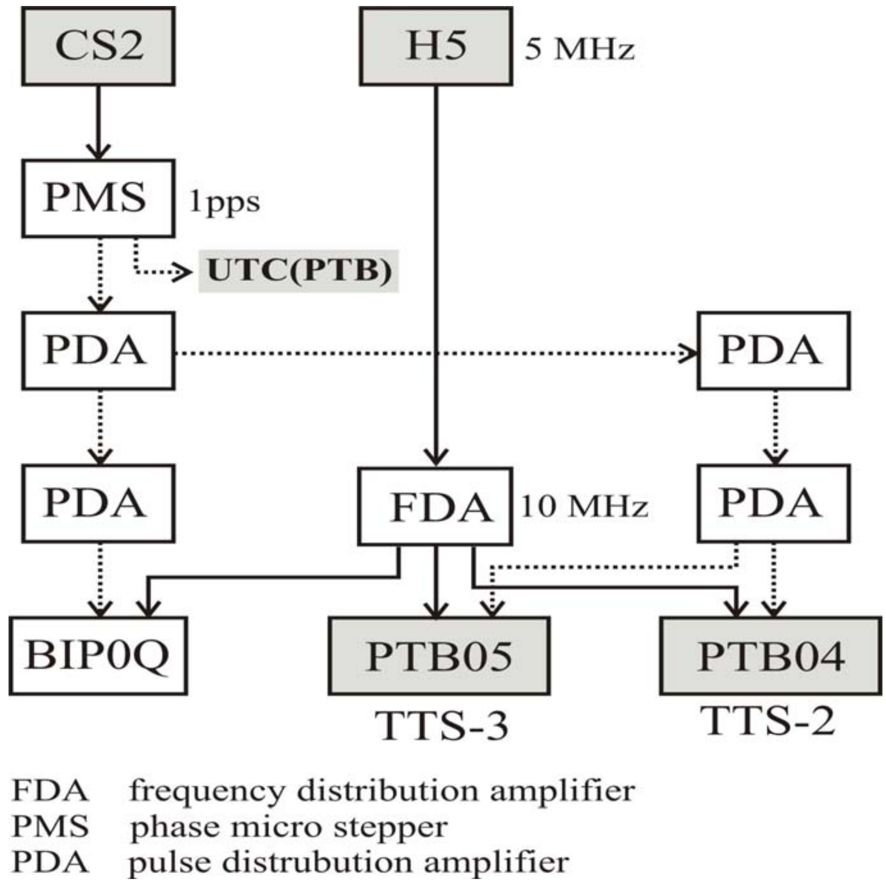
• Rise time of the local UTC pulse:	< 5 ns
• Is the laboratory air conditioned:	yes
• Set temperature value and uncertainty :	23.0 ± 0.5 °C
• Set humidity value and uncertainty :	Max. 50 %

Cable delay control

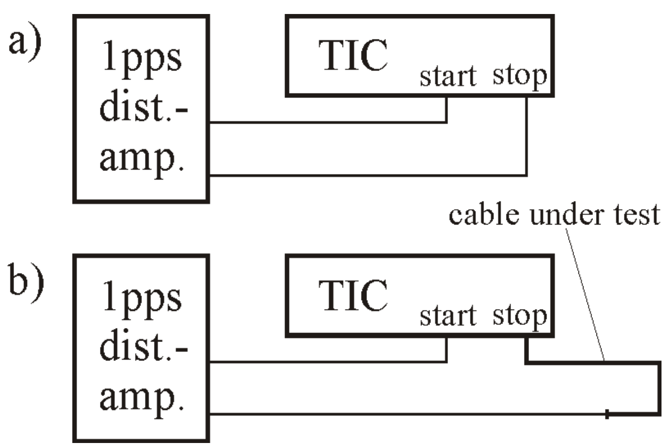
Cable identification	delay measured by BIPM	Delay measured by local method
BIPM C130	136.2 ns ± 0.4 ns	135.8 ns ± 0.1 ns

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:



cable delay = measurement b) – measurement a)

BIPM GPS calibration information sheet

Laboratory:	USNO
Date and hour of the beginning of measurements:	22 Feb 2007 (MJD 54153), 1854 UT
Date and hour of the end of measurements:	14 Mar 2007 (MJD 54173), 1149 UT

Receiver setup information

	Local:	**Portable: BP0Q**
• Maker:	AOS	AOS
• Type:	TTS-2	TTS-3
• Serial number:	S/N 014	012
• Receiver internal delay (GPS):	-40.1	30.5
• Receiver internal delay (GLO):	N/A	0.0
• Antenna cable identification:	LF	C130
Corresponding cable delay:	220.4	136.2 ns ± 0.4 ns
• Delay to local UTC:	0.0 ns	0.0 ns
• Receiver trigger level:	0.5 V	0.5 V
• Coordinates reference frame:	ITRF	ITRF
Latitude or X m	+1112162.140	+1112166.386
Longitude or Y m	-4842853.628	-4842851.429
Height or Z m	+3985496.084	+3985494.427

Antenna information

	Local:	**Portable:**
• Maker:	KW Microwave/AOA	Javad
• Type:	Dorne Margolin	MarAnt+
• Serial number:	KW5-0258	1713
If the antenna is temperature stabilised		
• Set temperature value :	-	-

Local antenna cable information

• Maker:	Andrews
• Type:	FSJ1-50A
• Is it a phase stabilised cable:	Yes
• Length of cable outside the building:	6 meters

General information

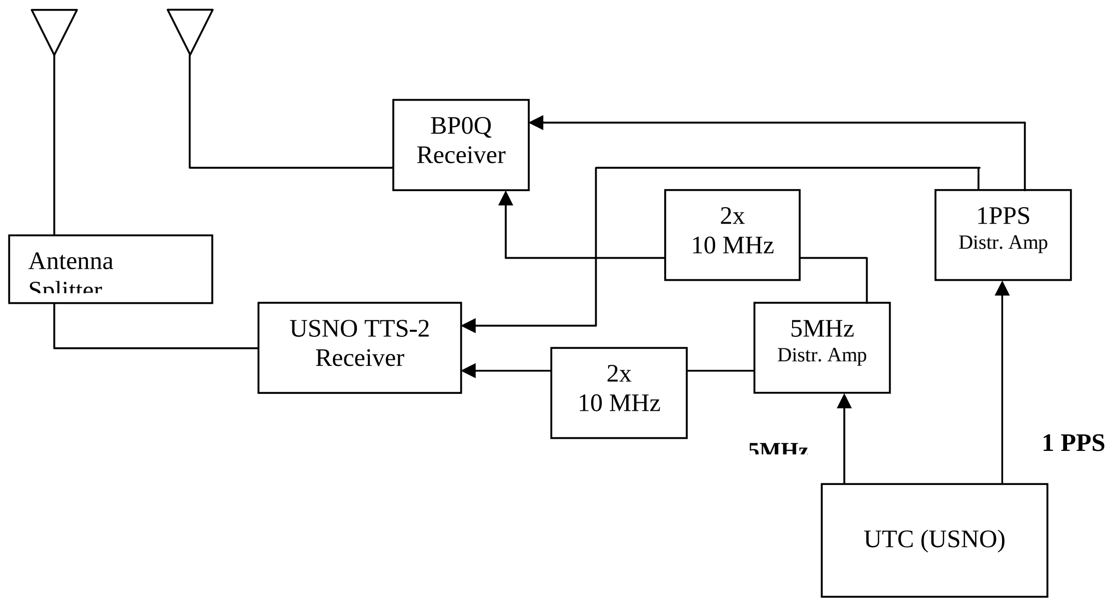
• Rise time of the local UTC pulse:	4.1 ns
• Is the laboratory air conditioned:	Yes
• Set temperature value and uncertainty:	25C, +/-1C
• Set humidity value and uncertainty:	13% to 24%

Cable delay control

Cable identification	Delay measured by BIPM	Delay measured by local method
BIPM C130	136.2 ns ± 0.4 ns	136.2 ns +/-200ps

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:

Appendix II

Measurement of portable cables at the visited laboratories

Laboratory	BIPM C123 cable /ns	Measurement method
BIPM	136.2 ns ± 0.4	Double Weight Pulse method
OP	-	-
PTB	135.8 ns ± 0.1	Pulse method
AOS	-	-
USNO	136.2 ns ± 0.2	-
IT	-	-

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	53979	-58.65	2.46	0.54	21
	53980	-59.55	2.38	0.36	45
	53981	-59.20	2.22	0.33	44
	53982	-59.37	2.38	0.50	23
PTB	53991	-61.48	1.75	0.008	424
	53992	-62.30	1.07	0.04	595
	53993	-61.91	1.34	0.05	616
	53994	-62.13	2.11	0.09	593
	53995	-61.89	1.75	0.07	603
	53996	-62.17	1.11	0.07	220
AOS	54003	-60.88	1.21	0.07	286
	54004	-60.99	1.27	0.05	545
	54005	-61.49	1.21	0.05	548
	54006	-60.73	1.62	0.07	547
	54007	-59.15	1.17	0.05	564
	54008	-60.78	1.88	0.08	581
	54009	-61.49	1.22	0.07	343
	54010	-61.47	1.14	0.05	550
	54011	-61.01	1.12	0.05	522
	54012	-60.98	1.13	0.05	537
	54013	-61.09	1.21	0.05	533
	54014	-61.21	1.12	0.05	532
	54015	-61.14	1.19	0.08	230
	54016	-61.46	1.18	0.07	277
	54017	-60.20	1.35	0.06	539
	54018	-61.14	1.24	0.05	539
	54019	-59.64	1.28	0.05	553
	54020	-60.07	1.18	0.05	543
	54021	-59.34	1.17	0.05	542
	54022	-60.51	1.54	0.06	562
	54023	-61.10	1.22	0.05	563
	54024	-61.31	1.34	0.06	476
	54025	-60.90	1.63	0.07	518
	54026	-60.08	1.32	0.06	542
	54027	-59.47	1.05	0.04	556
	54028	-59.43	1.20	0.05	553
	54029	-59.50	1.13	0.05	575
	54030	-59.33	1.33	0.06	574
	54031	-59.23	1.04	0.04	563
	54032	-59.10	1.17	0.05	553
	54033	-59.45	1.24	0.05	550
	54034	-59.89	1.34	0.06	565
	54035	-60.32	1.31	0.06	554
	54036	-60.27	1.26	0.05	557
	54037	-59.99	1.41	0.06	576
	54038	-58.65	1.22	0.05	557
	54039	-59.27	1.20	0.05	575
	54040	-59.85	1.28	0.05	559
	54041	-60.25	1.19	0.05	472

LAB	MJD	Mean offset /ns	Standard deviation of individual common view observations /ns	Standard deviation of the mean /ns	Number of individual common views
AOS	54042	-60.95	1.15	0.05	562
	54043	-61.06	1.32	0.09	220
	54044	-59.21	1.26	0.07	306
	54045	-59.44	1.17	0.05	556
	54046	-60.07	1.30	0.06	560
	54047	-60.38	1.22	0.05	556
	54048	-60.48	1.22	0.05	543
	54049	-60.64	1.30	0.05	561
	54050	-60.87	1.31	0.06	526
	54051	-59.55	1.67	0.07	561
	54052	-59.25	1.35	0.06	537
	54053	-59.92	1.25	0.05	567
	54054	-60.50	1.85	0.08	557
	54055	-60.48	1.50	0.06	556
	54056	-60.91	1.38	0.06	576
	54057	-58.64	1.40	0.06	574
	54058	-59.75	1.29	0.06	546
	54059	-60.17	1.24	0.05	541
	54060	-60.23	1.34	0.06	541
	54061	-60.35	1.21	0.05	484
	54062	-60.11	1.25	0.05	541
	54063	-60.10	1.18	0.05	552
	54064	-59.45	1.74	0.07	541
	54065	-60.86	1.34	0.06	532
	54066	-60.42	1.15	0.05	549
	54067	-60.02	1.27	0.05	561
	54068	-60.38	1.20	0.05	545
	54069	-60.85	1.29	0.05	562
	54070	-59.87	1.71	0.07	566
	54071	-60.52	1.30	0.05	572
	54072	-59.58	1.54	0.06	576
	54073	-60.34	1.29	0.05	565
	54074	-58.85	1.68	0.07	578
	54075	-60.00	1.58	0.07	559
	54076	-60.31	1.24	0.05	576
	54077	-60.25	1.15	0.05	561
	54078	-59.41	1.15	0.05	581
	54079	-58.34	1.17	0.05	552
	54080	-60.07	1.42	0.06	571
	54081	-59.97	1.26	0.05	556
	54082	-59.17	1.63	0.07	565
	54083	-59.90	1.24	0.05	550
	54084	-60.36	1.22	0.05	548
	54085	-59.66	1.33	0.06	548
	54086	-59.47	2.31	0.10	533
	54087	-61.20	1.37	0.06	548
	54088	-60.16	1.64	0.07	553
	54089	-60.21	1.31	0.06	563
	54090	-60.20	1.42	0.06	585
	54091	-60.37	1.36	0.06	596
	54092	-59.82	1.39	0.06	574
	54093	-60.70	1.19	0.05	580

LAB	MJD	Mean offset /ns	Standard deviation of individual common view observations /ns	Standard deviation of the mean /ns	Number of individual common views
AOS	54094	-60.74	1.36	0.06	580
	54095	-61.08	1.37	0.06	593
	54096	-60.95	1.17	0.05	535
	54097	-60.80	1.17	0.05	557
	54098	-60.37	1.63	0.07	567
	54099	-58.88	1.21	0.05	562
	54100	-59.63	1.19	0.05	547
	54101	-60.28	1.18	0.05	562
	54102	-60.56	1.19	0.05	519
	54103	-60.39	1.29	0.06	540
	54104	-59.33	2.10	0.09	540
	54105	-58.61	1.89	0.09	472
	54106	-60.65	1.30	0.06	520
	54107	-60.71	1.26	0.05	570
	54108	-61.20	1.48	0.07	515
	54109	-58.91	1.58	0.07	561
	54110	-58.26	1.40	0.06	522
	54111	-59.13	1.30	0.06	513
	54112	-59.61	1.45	0.06	529
	54113	-60.05	1.23	0.05	557
	54114	-60.56	1.13	0.05	566
	54115	-60.89	1.31	0.06	539
	54116	-60.89	1.19	0.07	268
USNO	54153	-61.02	1.17	0.10	134
	54154	-61.29	1.42	0.06	586
	54155	-61.38	1.45	0.06	581
	54156	-61.18	1.54	0.06	590
	54157	-61.34	1.50	0.06	579
	54158	-61.37	1.37	0.06	581
	54159	-60.33	1.78	0.07	588
	54160	-59.68	1.58	0.07	561
	54161	-60.12	1.24	0.05	554
	54162	-59.83	1.48	0.06	577
	54163	-59.83	1.47	0.06	579
	54164	-59.95	1.53	0.06	571
	54165	-59.63	1.39	0.06	568
	54166	-59.26	1.45	0.06	573
	54167	-59.58	1.39	0.06	585
	54168	-59.34	1.40	0.06	562
	54169	-59.22	1.66	0.07	546
	54170	-59.16	1.54	0.06	562
	54171	-59.76	1.45	0.06	580
	54172	-59.64	1.31	0.06	563
	54173	-59.33	1.42	0.08	284
IT	54404	-28.98	2.90	0.18	259
	54405	-28.86	2.94	0.11	671
	54406	-28.76	2.91	0.11	677
	54407	-28.57	2.95	0.11	669
	54408	-28.52	2.86	0.11	670
	54409	-28.16	2.90	0.16	350

LAB	MJD	Mean offset /ns	Standard deviation of individual common view observations /ns	Standard deviation of the mean /ns	Number of individual common views
OP	54627	-56.19	2.32	0.35	43
	54628	-56.85	1.81	0.28	42
	54629	-56.92	1.84	0.28	44
	54630	-56.38	1.92	0.29	45
	54631	-56.17	1.84	0.28	42
	54632	-56.01	1.29	0.20	41
	54633	-55.89	1.40	0.35	16