APMP Round-Robin Intercomparison of GPS Receiver Delays

Report on the First Round of the 2004 Campaign
Preliminary Draft for Discussion

R. B. Warrington, P. T. H. Fisk and M. J. Wouters

Australian Government

National Measurement Institute

PO Box 264
Lindfield, NSW 2070
Sydney, Australia

1. Introduction

Between January and July of 2004, NMI Australia coordinated an intercomparison of GPSCV time-transfer receivers at several APMP member institutes. The purpose was to compare the internal receiver delays by circulating a common travelling receiver among the participating laboratories. The portable receiver was developed by staff at NMI under contract to the Telecommunications Laboratories in Taiwan, who generously made the receiver available for the campaign.

This report summarizes the results of the intercomparison, based on processing carried out at NMI. These results should be regarded as preliminary until all of the participating laboratories have had an opportunity to comment on the results. All data and analysis files are available on the NMI FTP site.

2. Schedule

The schedule of the first round of the comparison is shown in Table 1, which also includes details of the host receiver at each laboratory. Additional information about the set-up of equipment at each location is provided in Appendix 1.

Following commissioning at NMI, the portable system was operated at BNM-SYRTE in Paris. The host receiver of the Observatoire de Paris (OP) there has acted as reference for previous intercomparisons coordinated by the BIPM. We adopt the internal delay of this receiver as the reference for this intercomparison.

The portable system was returned to NMI after operation at BNM-SYRTE and also at the end of the first round, to verify consistency of the measurements.

3. Comparison procedure

The portable time-transfer system is a variant of the systems developed at NMI based on the Javad/Topcon Euro-80 dual-frequency GPS receiver [1]. This system processes raw receiver and timing data to generate output files in the standard CCTF format [2], but can also generate geodetic observation files in the standard RINEX format [3] from the same data. These files can be used for accurate self-survey of antenna coordinates. All raw data is stored by the system, allowing post-processing with antenna coordinates of the highest precision; these only become available when the International GPS Service finalises high-precision orbitography for the GPS satellites, some time after the data is recorded.

The equipment circulated comprised the receiver, its antenna and an antenna cable of known delay. A line amplifier was also circulated, to compensate for additional attenuation where a longer antenna cable was needed. Each host laboratory supplied two signals to the portable system: a 10 MHz reference frequency, and a 1 pulse-per-second signal derived 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 host receiver.

CCTF data from both the host and portable receivers was returned to NMI for processing. The portable system includes a Zip drive, so that the larger raw data files could also be returned to NMI for post-processing. TL and NICT provided data for two host receivers during the comparison; in both cases, the analysis has only been carried out to date for one of the two.

Each laboratory was also invited to measure the delay of the portable system antenna cable, as a further check on the consistency of measurements. The results are shown in Table 2.

4. Data processing

Values for the offset between the host and travelling receivers were obtained for each laboratory, as follows.

1. Accurate antenna coordinates are first obtained for the portable system antenna, by submitting RINEX-format self-survey data to the AusPOS online processing service of Geoscience Australia [4]. Table 3 shows coordinates obtained for the portable system antenna at each laboratory in this way. It is hoped that these may be useful as a cross-check of host system antenna coordinates. A full report for each calculation is included in Appendix 2.

2. CCTF data for the portable system is regenerated using the precise antenna coordinates and the stored raw GPS and timing data. Tracks which were invalid for any reason (for example, where either receiver failed to maintain tracking for the full 13 minutes) are discarded.

3. We form the data set

   $$\varepsilon(t) = [\text{REF–SV}]_{A}(t) - [\text{REF–SV}]_{B}(t) \qquad (1)$$

   for all valid satellite tracks t common to both receivers A and B; quantities appearing in square brackets are taken from the corresponding data in the CCTF-format file. For the comparison at BNM-SYRTE, we form the difference APMP–OP (that is, we choose A≡APMP, denoting the portable receiver, and B≡OP) to transfer the calibrated internal delay of the OP receiver to the portable receiver (see (6) below). For all other comparisons we choose A as the host receiver and B≡APMP, and use the portable receiver delay to establish a comparison value for the host receiver.

4. We calculate a mean offset $\overline{\varepsilon(t)}$ for the comparison by linear regression (see plots in Appendix 3), where we include a linear as well as a constant term in the fit to $\varepsilon(t)$. The linear term accounts for any slow variation in offset between the two receivers. For completeness, we carry out the regression twice: once with all tracks weighted equally, and once weighting each track t by $[\text{DSG}]_{A}(t)^{-2}$. The [DSG] values give the RMS scatter of one-second measurements of [REF–GPS] over a 13-minute track [2], and the weighted fit reduces the contribution of tracks with large scatter to $\overline{\varepsilon(t)}$.

   Values for $\overline{\varepsilon(t)}$ obtained from both weighted and unweighted fits are shown in Appendix 3. The agreement is very good in all cases, implying that the simple regression is not distorted by any outliers or other anomalies in the data set $\varepsilon(t)$. We therefore adopt the values of $\overline{\varepsilon(t)}$ obtained from the unweighted fits as an appropriate estimate of the mean offset in [REF–SV] between the two receivers.

5. We correct for any difference between delay values as reported by the host laboratory and as used internally by a GPS receiver. This correction is necessary to deal with cases where parameters were measured or corrected after the CCTF data were recorded. 'Reported' values are those shown in Appendix 1, and 'internal' values are those appearing in the header of the CCTF data files. It should be clearly understood that we take the delays reported by the laboratory as the true values. All delays are summarized in Table 4.

   The delay correction applied in processing to generate the CCTF data is

   $$[\text{REF–SV}] = (\text{REF–SV})_{\text{Raw}} - [\text{INT DLY}] - [\text{CAB DLY}] + [\text{REF DLY}] \qquad (2)$$

   so that to account for changes in any of these delay parameters we calculate corrected values [REF–SV]′ :

$$
\begin{aligned}
[\text{REF–SV}]' &= [\text{REF–SV}] + \delta \qquad (3)\\
\delta &= -[\text{INT DLY}]_{\text{Reported}} + [\text{INT DLY}]_{\text{Internal}}\\
&\quad -[\text{CAB DLY}]_{\text{Reported}} - \delta_{\text{AMP}} + [\text{CAB DLY}]_{\text{Internal}}\\
&\quad +[\text{REF DLY}]_{\text{Reported}} - [\text{REF DLY}]_{\text{Internal}}
\end{aligned}
$$

where δ_{AMP} is an additional correction applied for the line amplifier, if used (§5.5). We follow the convention that [CAB DLY] refers to the delay of the antenna cable only; [INT DLY] includes contributions from the internal delay of both the receiver and antenna, the latter being difficult to measure directly.

Combining (2) and (3) we obtain

$$
\begin{aligned}
\varepsilon(t)' &= [\text{REF–SV}]_A(t)' - [\text{REF–SV}]_B(t)' \qquad (4)\\
&= ([\text{REF–SV}]_A(t) + \delta_A) - ([\text{REF–SV}]_B(t) + \delta_B)\\
&= \varepsilon(t) + \delta_A - \delta_B
\end{aligned}
$$

so that the mean offset after correcting for delays is

$$
\begin{aligned}
\overline{\varepsilon(t)}' &= \overline{\varepsilon(t)} + \delta_A - \delta_B\\
&\equiv \Delta
\end{aligned}
$$

6. If all delays are known we expect the corrected offset Δ to be zero. Any non-zero value can therefore be used to transfer a calibrated value for the internal delay of one receiver to the other. From (3) and (4) we write

$$
\begin{aligned}
\varepsilon(t)'' &= \varepsilon(t)' - \Delta \text{ so that } \overline{\varepsilon(t)}'' = 0\\
[\text{REF–SV}]_A'' &= [\text{REF–SV}]_A(t)' - [\text{INT DLY}]_{\text{A, True}} + [\text{INT DLY}]_{\text{A, Reported}}\\
[\text{INT DLY}]_{\text{A, True}} &= [\text{INT DLY}]_{\text{A, Reported}} + \Delta
\end{aligned}
$$

5. Details of data processing for individual laboratories

5.1. NMI (1)

Between 52977 and 53012, the portable system was operated with the line amplifier between the antenna and antenna cable, to estimate the amplifier delay (§5.5). Data in this period were corrected for the measured amplifier delay of δ_{AMP}=0.7 ns obtained from this data set.

5.2. BNM-SYRTE

The comparison is made in the opposite sense to the other laboratories: the portable receiver internal delay is obtained from the host receiver, rather than the other way around (§4).

5.3. NMI (2)

Between 53093 and 53096, the portable system was operated with the line amplifier between the antenna and antenna cable, to assist with estimating the amplifier delay (§5.5). Data in this period were corrected by the measured amplifier delay of of δ_{AMP}=–1.9 ns obtained from this data set.

5.4. TL

An unknown signal near the GPS L2 frequency was observed at TL during the comparison (Figure 1). Data recorded by both the host and portable receivers show the effects of interference (see Appendix 3). It was possible to identify regions which appeared free of interference by comparing values for [DSG] and [ISG] to those obtained for similar receivers in other locations. [DSG] and [ISG] give the RMS scatter of one-second values of [REF–GPS] and the measured ionospheric delay [MSIO] (respectively) over a 13-minute track [2]. Data selected in this way are shown in black in the data plots in Appendix 3, and data excluded for suspected interference are shown in a different colour.

5.5. SPRING

For the current comparison, the line amplifier was only used at SPRING, where a long antenna cable was needed for the portable system; all other laboratories used the antenna cable supplied. It is necessary to compensate for any change in apparent antenna cable delay with the line amplifier installed. This change was estimated by measuring the shift in a zero-baseline comparison between the portable and host receivers when the amplifier was inserted and then removed (see Figure 2).

These measurements were made three times at NMI, obtaining delays δ_{AMP} of –0.7, –1.9 and –0.2 ns. The same cable configuration was used in each case, so that the apparent variation is due to the amplifier only. Note that, based on the data shown in Figure 2, the line amplifier appears to *reduce* the apparent cable delay ($\delta_{AMP}<0$). A value of $\delta_{AMP}=(-1\pm1)$ ns has been adopted for the delay correction to be applied at SPRING.

We note here that we are unable to distinguish between two contributions to δ_{AMP} which both arise in principle: one due to a simple internal delay of the amplifier itself, and the other due to any variation in the internal delay of the receiver as a function of the input GPS signal level. To our knowledge the latter effect has not been measured for any receiver. It is possible that such an effect may account for the sign and moderate scatter of values for δ_{AMP} obtained at NMI. We also note that we are not able to evaluate any possible contribution from this effect due to different GPS reception conditions between NMI, where the delay was measured, and SPRING, where the amplifier was used.

6. Results and discussion

Results are shown in Tables 3–6. We reiterate that these should be regarded as provisional until participating laboratories have had opportunity to review and comment. In particular, any inadvertent error in the delay values shown in Table 4 (for example, any transcription error made during analysis at NMI) will affect the final value obtained for the host receiver internal delay.

6.1. General observations

It is not possible to give an uncertainty in the values obtained for internal receiver delays. This uncertainty includes at least three contributions: uncertainty in the internal delay adopted for the portable receiver obtained from the comparison at BNM-SYRE, in delay parameters as measured by the host institutes, and in the mean offset obtained from the comparison at each institute. The last contribution should be carefully evaluated with reference to the statistical properties of the corresponding recorded data.

The level of consistency between results obtained for the three comparisons at NMI is very good, with closure to approximately one nanosecond between the beginning and end of the round. This is an encouraging result, and gives confidence in the performance and stability of the portable system. We note that for a recent intercomparison coordinated by BIPM [5], closure was obtained at the level of 4 ns.

6.2. Specific results

The host receiver at NMI, a Topcon Euro-80 dual-frequency receiver, has a nominal internal delay of 46.5 ns. This value is regarded as provisional, as it was obtained by transfer from an AoA TTR6 receiver (serial number 446), and the uncertainty in the internal delay of this receiver is relatively large [7]. The offset obtained for the NMI host receiver consequently appears reasonable.

The agreement with the results of independent comparisons undertaken by BIPM [5, 6] is also encouraging. The most recent comparison obtained a differential correction of (+9 ± 4) ns to be applied to UTC(AUS) – UTC(OP) [5], or equivalently to the internal delay of the NMI receiver taking the OP receiver as reference. In addition, an earlier comparison obtained a differential correction of (+8.8 ± 3.0) ns for UTC(KRISS) – UTC(OP) [6]. The nominal value for the KRISS host receiver, an NMI/Topcon dual-frequency receiver, was obtained by transfer from the NMI receiver during commissioning at NMI. All three offsets (this comparison, [5] and [6]) are in good agreement.

We note that this offset obtained for the NMI receiver will also appear as a contribution to the offset obtained for the host receivers at both NICT and SPRING. This is because the reported values for the internal delays of both receivers were similarly obtained by transfer from the NMI receiver during commissioning at NMI. Regarding the remaining offset of approximately 4 ns at SPRING, we observe that the host receiver is a single-frequency Motorola Oncore, and the comparison data consequently exhibits a larger RMS scatter (6 ns, compared to 2 ns typically obtained from dual-frequency receivers in this comparison).

The most likely cause for the relatively large offset obtained for the host receivers at NICT and NMIJ is a misinterpretation by NMI of the delay information provided by these laboratories.

The internal delay of the TL host receiver was also obtained during commissioning at NMI, but in this case by transfer from the BIPM H travelling receiver which was fortuitously hosted by NMI at this time [5]. The offset of 9 ns obtained for the NMI host receiver is therefore not expected. The consistency between values obtained by the two independent comparisons is again good, particularly in view of the closure uncertainty of the BIPM campaign noted above.

6.3. Future intercomparisons

The performance of the new portable receiver appears encouraging. Previous APMP intercomparisons have suffered from poor reliability of the travelling receiver [7]; no such difficulty has been encountered with the portable system in the current round.

Approximately one week of data collection at each host laboratory appears sufficient. No significant changes therefore appear necessary to either the portable system itself or to the comparison procedure for future campaigns.

7. Conclusion

There now exist multiple independent comparisons among receivers at APMP member laboratories (Figure 3). These include comparisons conducted by the APMP itself [7, and this work], by BIPM [5, 6], and by individual laboratories (for example, transfer calibrations undertaken during commissioning of new receivers at NMI). This network provides a wealth of information to assess the consistency of results and to study the stability of receiver delays over time.

We hope that the current intercomparison contributes to maintaining the integrity of time transfer in and beyond the Asia-Pacific region, and we look forward to continuing this important work together in the future.

8. Acknowledgements

The authors wish to express their gratitude to their colleagues in all participating laboratories for their dedicated and highly professional cooperation during the intercomparison. We thank Dr Liao of TL for generously making the portable receiver system available, and we are grateful to Dr Liao and to Dr Imae of NMIJ for their support through the work of the APMP TCTF.

9. References

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[3] http://www.navcen.uscg.gov/pubs/gps/rinex/

[4] http://www.ga.gov.au/nmd/geodesy/sgc/wwwgps/

[5] W. Lewandowski and P. Moussay, *Rapport* BIPM-2003/05.

[6] W. Lewandowski and L. Tisserand, *Rapport* BIPM-2004/06.

[7] P. T. H. Fisk and R. B. Warrington, 'Report on the APMP Round Robin GPS Common-View Time Transfer Receiver Intercomparison Experiment': 'Round 1: October 1999 to May 2000', 'Round 2: March 2001 to July 2001', and 'Interim Appendix' (2002).

	Host receiver	Serial number	Start		Stop	
NMI (1)	NMI/Topcon	8RQRFKXT534	52970	27/11/03	53029	25/01/04
BNM-SYRTE	AoA TTR5	051	53062	27/02/04	53075	11/03/04
NMI (2)	NMI/Topcon	8RQRFKXT534	53082	18/03/04	53101	6/04/04
TL	NMI/Topcon	8RJJBNWROCG	53115	20/04/04	53128	3/05/04
	AoA TTR6	479				
NICT	NMI/Topcon	8PN45EETDKW	53142	17/05/04	53149	24/05/04
	AoA TTR6	451				
NMIJ	AoA TTR6	484	53151	26/05/04	53156	31/05/04
SPRING	NMI/Oncore		53164	8/06/04	53172	16/06/04
NMI (3)	NMI/Topcon	8RQRFKXT534	53180	24/06/04	53208	22/07/04

Table 1: Schedule of the first round of the intercomparison.

	NML IF delay (ns)	Measurement method
NMI (1)	159.8 ± 1.0	Time-interval counter
BNM-SYRTE		
TL	159.0 ± 1.5	Network analyser
NICT		
NMIJ		
SPRING	158.5 ± 2.0	Time-interval counter
NMI (3)	159.3 ± 1.0	Time-interval counter

Table 2: Values obtained for the delay of the portable system antenna cable from measurements made by host laboratories.

	ITRF2000	Cartesian			Geodetic, GRS80 ellipsoid							Baseline
	@	X (m)	Y (m)	Z (m)	Latitude			Longitude			Height (m)	(m)
NMI (1)	18/12/03	-4648204.271	2560477.026	-3526504.952	-33°	-46′	-58.1539″	151°	9′	6.1177″	99.072	8.067
		0.007	*0.007*	*0.006*			*0.001 m*			*0.006 m*	*0.010*	*0.012*
BNM-SYRTE	1/03/04	420783.525	171637.812	4778657.541	48°	50′	9.1056″	2°	20′	5.7574″	124.628	4.687
		0.002	*0.004*	*0.004*			*0.002 m*			*0.005 m*	*0.004*	*0.006*
NMI (2)	21/03/04	-4648204.276	2560477.037	-3526504.944	-33°	-46′	-58.1534″	151°	9′	6.1174″	99.076	8.060
		0.009	*0.008*	*0.008*			*0.003 m*			*0.004 m*	*0.014*	*0.014*
TL	24/04/04	-2994425.895	4951311.783	2674496.617	24°	57′	12.8151″	121°	9′	52.0875″	202.329	13.592
		0.010	*0.017*	*0.018*			*0.009 m*			*0.025 m*	*0.025*	*0.027*
NICT	22/05/04	-3942161.308	3368285.880	3701886.725	35°	42′	23.9392″	139°	29′	18.7997″	131.323	4.886
		0.001	*0.001*	*0.002*			*0.001 m*			*0.000 m*	*0.002*	*0.002*
NMIJ	28/05/04	-3962302.243	3308875.364	3733523.235	36°	3′	32.0393″	140°	8′	6.4005″	78.502	12.763
		0.002	*0.001*	*0.003*			*0.003 m*			*0.001 m*	*0.001*	*0.004*
SPRING	11/06/04	-1519458.890	6192913.814	142851.472	1°	17′	31.1958″	103°	47′	7.6451″	66.579	7.632
		0.013	*0.009*	*0.004*			*0.004 m*			*0.013 m*	*0.009*	*0.016*
NMI (3) †	27/06/04	-4648199.675	2560483.895	-3526506.097	-33°	-46′	-58.1976″	151°	9′	5.7977″	99.117	0.977
		0.008	*0.017*	*0.008*			*0.001 m*			*0.014 m*	*0.014*	*0.020*

† The antenna was placed on a different mount point to that used for NMI (1) and (2).

Table 3: Precise antenna coordinates obtained from self-survey of the portable receiver for each comparison, in the ITRF2000 coordinate frame at the reference time indicated. These coordinates are obtained from RINEX-format data files generated by the portable time-transfer system and submitted to AusPOS, the online service provided by Geoscience Australia. Coordinate uncertainties in metres are shown in italics, and are typically below one centimetre. The baseline shown is the distance between portable and host antennas, where the latter are taken from the header of the CCTF-format data files.

	Host receiver						Travelling receiver						
	Reported			Internal			Reported				Internal		
	INT	REF	CAB	INT	REF	CAB	INT	REF	CAB	AMP	INT	REF	CAB
NMIA (1)	46.5	76.	75.9	46.5	68.9	75.9	44.79	85.9	159.8	0.0	44.79	85.64	159.8
BNM-SYRTE	54.	304.	168.	54.	304.	168.	44.79	306.	159.8	0.0	44.79	85.64	159.8
NMIA (2)	46.5	76.	75.9	46.5	68.9	75.9	44.79	85.9	159.8	0.0	44.79	85.64	159.8
TL	45.1	30.7	119.1	45.1	30.7	119.1	44.79	37.6	159.8	0.0	44.9	37.6	159.8
NICT	47.2	344.123	152.15	47.2	344.123	152.15	44.79	319.97	159.8	0.0	44.9	319.97	159.8
NMIJ	50.	27.	259.	50.	27.	259.	44.79	510.6	159.8	0.0	44.9	510.6	159.8
SPRING	-30.	14.8	344.	-30.	16.	344.	44.79	72.	270.	-1.0	44.9	72.	270.
NMIA (3)	46.5	76.	75.9	46.5	68.9	75.9	44.79	85.9	159.8	0.0	44.79	85.64	159.8

Table 4: Values for receiver delay parameters provided by participating laboratories (‘reported’) and obtained from the header of the CCTF-format data files (‘internal’). The column labelled AMP holds values for the line amplifer delay δ_{AMP} (§5.5).

			Offset					Correction (ns)			
			Tracks	Midpoint	Mean (ns)	RMS (ns)	Slope (ps/day)	Host	Portable	Total	Δ
NMIA (1)	–	APMP	19526	53000.0	0.6	2.0	-3 ± 1	7.1	–0.26	6.84	7.44
APMP	–	**BNM-SYRTE**	539	53068.9	–232.1	2.6	40 ± 30	0.0	220.36	220.36	–11.74
NMIA (2)	–	APMP	5809	53091.6	0.6	2.0	–30 ± 5	7.1	–0.26	6.84	7.44
TL	–	APMP	1342	53121.0	–3.8	0.9	36 ± 13	0.0	–0.11	–0.11	–3.91
NICT	–	APMP	2252	53145.6	25.4	1.9	–59 ± 21	0.0	–0.11	–0.11	25.29
NMIJ	–	APMP	230	53153.6	52.7	2.4	–56 ± 104	0.0	–0.11	–0.11	52.59
SPRING	–	APMP	2691	53168.1	15.4	6.1	–23 ± 52	–1.2	–0.11	–1.31	13.09
NMIA (3)	–	APMP	9058	53194.6	1.9	2.2	–24 ± 3	7.1	–0.26	6.84	8.74

Table 5: Results obtained from comparison data (see §4). Mean offset, RMS and slope values are obtained from a linear regression to the difference of all common tracks, calculated in the sense indicated, with the mean evaluated at the midpoint. The final mean offset Δ includes corrections for host and portable receivers to account for changes to receiver delay parameters.

	Receiver internal delay (ns)		
	Reported	Δ	Comparison
NMIA (1)	46.5	7.44	53.9
APMP	44.79	−11.74	33.1
NMIA (2)	46.5	7.44	53.9
TL	45.1	-3.91	41.2
NICT	47.2	25.29	72.5
NMIJ	50.	52.59	102.6
SPRING	−30.	13.09	−16.9
NMIA (3)	46.5	8.74	55.2

Table 6: Comparison values for the internal delay for receivers participating in the intercomparison, obtained from the reported value plus the offset Δ from Table 5.

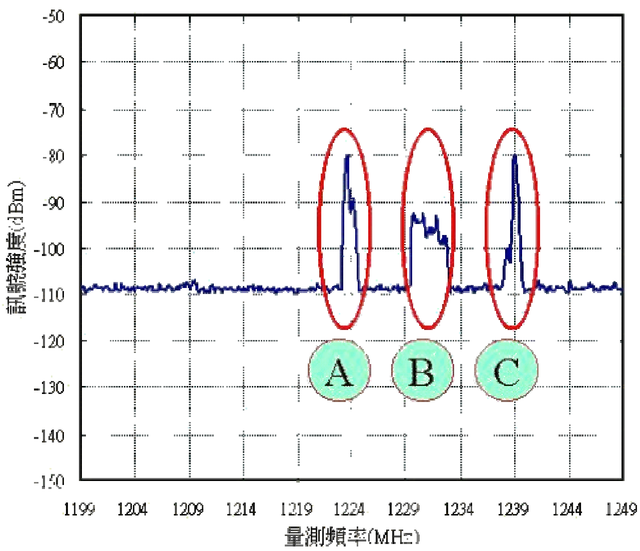

Figure 1: Unknown signal observed at TL near the GPS L2 frequency (1227.6 MHz).

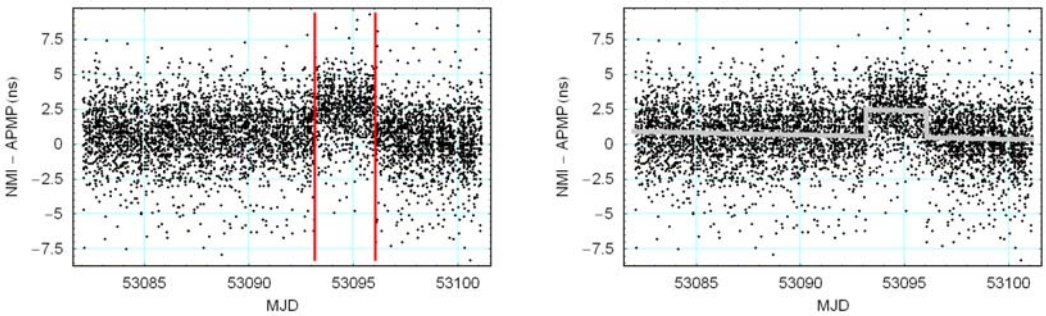

Figure 2: Estimating the delay correction for the line amplifier from a zero-baseline comparison conducted at NMI. The same data are shown in both plots. The solid line at right is a fitted step function with a variable slope. A value of δ_{AMP}=–1.9 ns is obtained from these data.

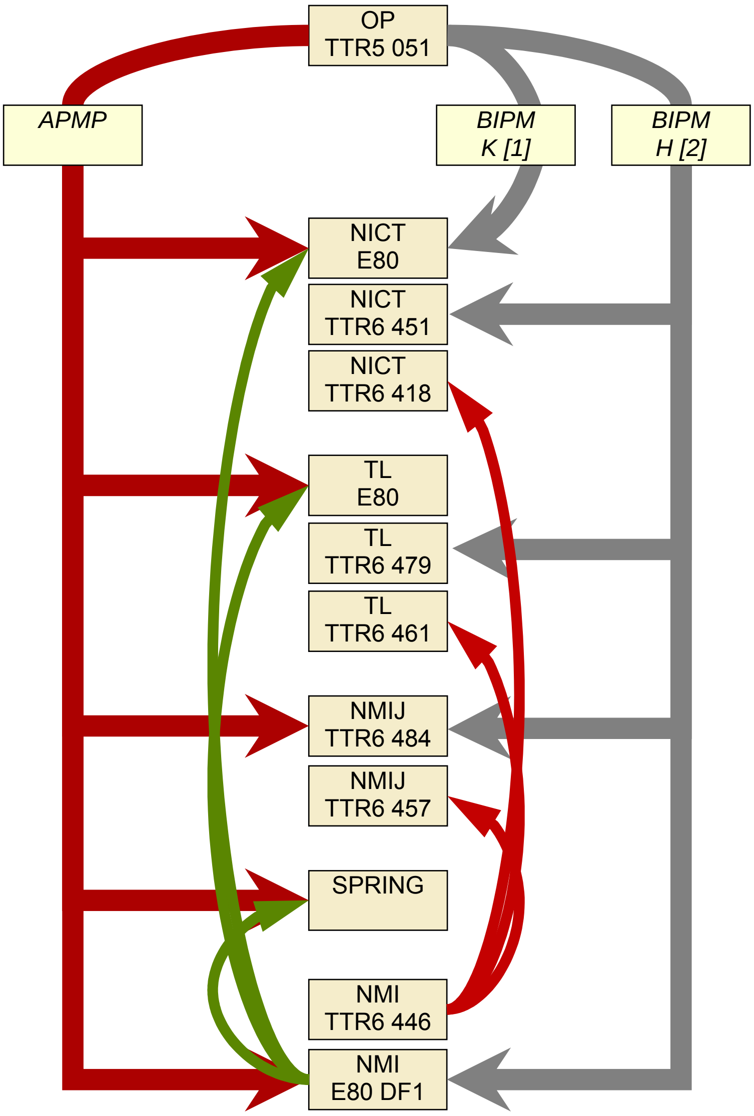

Figure 3: Independent delay comparisons among APMP receivers: ▬ first round of current campaign; — transfer calibration when receiver commissioned at NML; — APMP campaign 1999-2001 (TTR6); ▬ previous BIPM campaigns.