GPS Activities at NML Australia

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Abstract

The CSIRO National Measurement Laboratory (NML) has been actively pursuing the development of flexible and reliable GPS based systems for precise time and frequency transfer. This paper outlines recent progress with these systems, together with some applications. Revised results are also presented for a round-robin comparison of GPS receivers at APMP institutes following the recent visit to NML of a BIPM receiver with a calibrated internal delay.

1. Introduction

For several years NML has been developing systems for GPS Common View (GPSCV) time and frequency transfer. These systems aim to provide a turnkey solution for customers requiring high-accuracy and high-integrity traceability from a remote Cs or Rb frequency standard to a National Measurement Institute (NMI), without the need to ship the standard to the NMI for calibration.

The NML Timing System in its basic form consists of an Intel PC running the Linux operating system, a GPS receiver board and antenna, and a counter-timer (see Figure 1 (a)). The design philosophy is to use commercial and relatively generic hardware throughout, and to make the software hardware-independent as far as possible [1]. This provides significant flexibility for future upgrades as customer requirements and available technology evolve. Raw pseudorange and ephemeris data from the GPS receiver is processed using standard algorithms prescribed by BIPM's Consultative Committee on Time and Frequency [2]. Because the system is controlled by a host computer, it can perform many other functions in addition to time and frequency transfer, and can readily be monitored and maintained remotely via the internet or a telephone connection. Software and hardware extensions can be configured to support operation of these systems as Network Time Protocol Servers, data loggers, and GPS integrity monitoring stations.

Twenty-five of these systems are presently in operation, including eleven outside Australia, representing a total of approximately forty system-years of operation. A further four systems are scheduled to be commissioned in the near future. With the permission of the owners, data from many of these systems is made available at the NML FTP site (ftp://time1.tip.csiro.au/pub/) and circulated in a weekly email bulletin; please contact the authors if you would like to be added to the distribution list.

2. Recent Developments

2.1. Operation with the Topcon Euro-80 GPS receiver

Because the GPS common-view technique involves the comparison of electrical pseudoranges

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with geometric ranges to individual satellites, a receiver which can output extensive raw GPS data is required. The NML Timing System was originally developed using the Motorola Oncore VP, until Motorola discontinued production of this receiver in 2000. The Topcon (formerly Javad) Euro-80 receiver was selected as a suitable replacement, in part because it is capable of both single- and dual-frequency operation.

The performance of the NML Timing System using the Topcon Euro-80 receiver has been evaluated in several ways. Firstly, the RMS noise of REF–GPS data in CCTF-format output files generated by the system is only 1.15 ns when connected to a GPS satellite simulator. This gives an estimate of the performance of the receiver itself in the absence of additional propagation noise. Secondly, a zero-baseline comparison between CCTF-format output files generated by a single-frequency NML system and by an Allan Osborne TTR6A gives an RMS noise of 3.2 ns about the mean. This data was recorded under typical conditions, and the noise value includes contributions from both receivers. The mean offset can be used to transfer a calibrated value for the internal receiver delay from one receiver to another, and will be zero if all delays are known accurately. Finally, typical data recorded from both single- and dual-frequency NML Timing Systems are compared in Figure 2, along with data from a 3S Navigation R-100T receiver over the same period. The raw GPS data recorded by the NML system can also be post-processed using IGS precise ephemerides in place of the lower-precision ephemerides included in the GPS broadcast data stream; the consequent reduction in RMS noise is apparent in the figure.

Note that the internal delay of the receiver is different for the L1 and L2 signal paths. An additional characteristic delay representing the differential offset between the two signal paths must therefore be calibrated for each individual receiver, as well as the usual L1 internal delay measured for single-frequency receivers. We have calibrated this L1-L2 offset for one of the NML Euro-80 receivers using a GPS satellite simulator; this calibration can be transferred to another receiver in a zero-baseline comparison, just as for the L1 internal delay. Alternatively, a value for the L1-L2 offset may be deduced by comparing L1 and L2 pseudoranges at times of day when the ionospheric delay is expected to be minimal. This approach has been shown to yield values in reasonable agreement with the calibrated value obtained using the simulator.

A study of the temperature dependence of the internal delays of the system is in progress.

2.2. Generation of geodetic survey data in RINEX format

Because all raw GPS data recorded is stored by the NML Timing System, software extensions to generate observation data in RINEX format are comparatively straightforward; this software was developed in March 2002. Dual-frequency carrier phase geodetic survey data can therefore be recorded by any NML Timing System equipped with a dual-frequency receiver, and these data can be post-processed to obtain accurate values of the antenna coordinates. Figure 3 shows the output of an online processing service provided by Geoscience Australia. Three days of dual-frequency RINEX-format data recorded by an NML Timing System in operation at the BIPM in Paris, France were processed using IGS final orbit ephemerides. The 1-σ coordinate uncertainty reported by the Geoscience Australia processing software is approximately 1 cm.

This facility opens up several important applications. In particular, the same NML Timing System can now function as both a GPS Common-View time transfer station and a station in the International GPS Service (IGS) network, provided that the IGS requirements for antenna monumentation are satisfied. Additional systems with these capabilities installed around the

Pacific region would help to extend the IGS network, which appears to be relatively sparse in this region. This might also improve the characterization of IGS ionospheric maps in the Asia-Pacific region, which are important for high-precision time-transfer to equatorial locations because of the significant fluctuation in ionospheric delay at these latitudes. If the only available information on the real-time effects of the ionosphere is the parameter set broadcast in the GPS data messages, the effect on GPS time transfer can be significant. For example, the effect of ionospheric activity in the region of Malaysia compared with that in the region of Sydney, Australia, is strikingly apparent in Figure 4.

NML also intends to develop a portable system which can be used for surveying the antenna locations at remote sites with high precision.

3. APMP Round-Robin Comparison

Between September 2000 and August 2001, NML coordinated an intercomparison of GPSCV time transfer receivers at APMP member institutes. The purpose of this experiment was to compare the internal receiver delays by circulating a common travelling receiver among the participating laboratories. At the time of the comparison, the internal delay of the travelling receiver was not known, so the data only afforded a relative comparison.

A similar intercomparison exercise in the region was recently conducted by BIPM between NMIJ, NTSC, CRL, TL and NML. As part of this intercomparison, a BIPM TTS-2 multichannel CVGPS time-transfer receiver (BIPM H) was operated at NML for a short period in September 2002. The calibrated value for the internal delay of this receiver could be transferred to NML receivers, and subsequently to others from the APMP intercomparison by a reanalysis of recorded data.

3.1. Data Analysis

As in the original analysis of the APMP intercomparison, raw REF–GPS values from each receiver for each 780-second common-view track were corrected for any difference between delay parameters adopted by the receiver and those reported by the host laboratory:

$$\begin{aligned} \mathrm{REFGPS} &= \mathrm{REFGPS}_{\mathrm{raw}} - \Delta \\ \Delta &= (\delta_{\mathrm{INT}} + \delta_{\mathrm{ANT}} - \delta_{\mathrm{REF}})_{\mathrm{reported}} - (\delta_{\mathrm{INT}} + \delta_{\mathrm{ANT}} - \delta_{\mathrm{REF}})_{\mathrm{receiver}} \end{aligned}$$

where δ_{INT} is the internal delay of the receiver, δ_{ANT} is the time delay of the receiver's antenna and antenna cable, and δ_{REF} is the delay between the host realization of UTC 1 pps signal and the 1 pps input connector on the receiver. In practice, the separate contributions to δ_{ANT} from the antenna cable and the antenna itself are hard to separate; NML adopts the convention that δ_{ANT} represents the antenna cable delay only, equivalent to including the unknown antenna delay within the internal receiver delay. 'Reported' values are those reported directly to NML by the host laboratory, and 'receiver' values are those appearing in the CCTF-format data file header. This correction is necessary to account for revised or re-measured values of delay parameters obtained after the CCTF data was recorded. In all cases, reported values are taken to be correct.

Differences $\varepsilon(t)$ between REF–GPS values recorded by host and travelling receivers are calculated, discarding invalid tracks (for example, any incomplete track for either receiver):

$$\varepsilon(t) = \mathrm{REFGPS}_{\mathrm{Host}}(t) - \mathrm{REFGPS}_{\mathrm{Trav}}(t)$$

A least-squares linear fit to $\varepsilon(t)$ gives the mean offset evaluated at the midpoint of the recording period, a rate of change of this offset and the root mean square (RMS) deviation of the data about the fitted line. Raw data and calculations are available for inspection at ftp://time1.tip.csiro.au/pub/timedata/gps/APMP_data/GPS_calibration.

3.2. Transfer of Calibration

The travelling receiver circulated among APMP laboratories was an Allan Osborne TTR6 owned by NML with serial number 267. This receiver failed during the second round of the intercomparison and therefore could not be directly compared to BIPM H, the calibrated receiver circulated by BIPM. Instead, a second TTR6 receiver at NML with serial number 446 was first compared to BIPM H, yielding a calibrated internal delay of 53.5 ns, and 446 was then compared to 267 using previously recorded data. Internal delays obtained for 267 from data recorded at the beginning (September 1999) and end (May 2000) of the first round of the intercomparison were consistent, and a value of 58.6 ns was therefore adopted for the first round. A slightly different value was obtained from data recorded at the beginning of the second round (January 2001), and this value of 56.6 ns was therefore used.

3.3. Results

Results are presented in Figure 5 and Tables 1–3. These results show that the internal delays obtained for TTR6 receivers are generally consistent, falling within a range of approximately 50–60 ns. The most likely cause for the values for NAO, NRML and VMI falling outside this range is a misinterpretation by NML of the delay data provided by these laboratories, which are therefore encouraged to review NML's calculations available at the FTP site mentioned above. We note also that some laboratories appear to have adopted the value of 250 ns given for the antenna and antenna cable delay in the TTR6 user manual, which may indicate a different convention for this quantity from that adopted by NML as described above.

It is not possible to give an uncertainty in the values obtained for internal receiver delays, as NML does not have details of the uncertainty in delay parameters as measured by the host institutes. We estimate a minimum uncertainty of ±2 ns, due to uncertainty in the internal delay adopted for the travelling receiver. This estimate should be increased by contributions from measurements of delay parameters as noted, and also from the comparison between travelling and host receivers. The latter contribution should be carefully evaluated with reference to the statistical properties of the corresponding recorded data.

Acknowledgments

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References

[1] Fisk P. *et al*, 2000, *Proceedings of the Asia-Pacific Workshop on Time and Frequency*, 107.
[2] Allan D. W. and Thomas C., 1994, *Metrologia* **31**, 69-79.

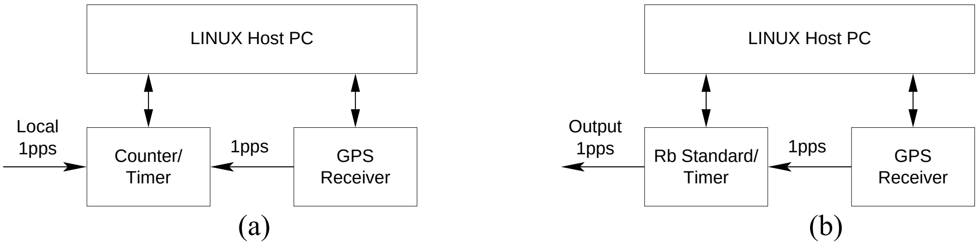


Figure 1: Sample configurations of the NML Timing System: (a) GPSCV time-transfer of a local reference; (b) using a Rb standard with integral timer such as the Stanford Research Systems PRS10 as a reference for a remote Network Time Protocol server**.**

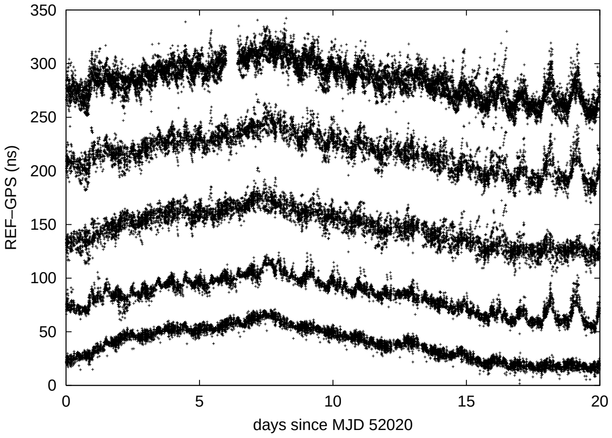
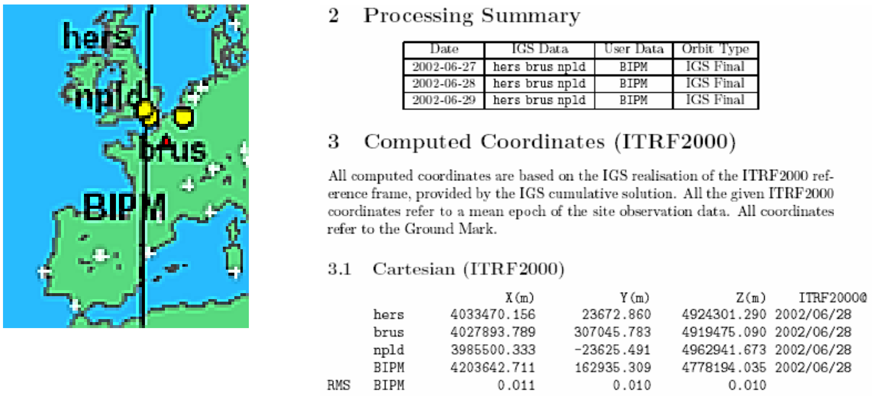


Figure 2: A comparison of different receivers and methods of GPS data processing. From the top, five curves are shown offset for clarity: (i) a 3S Navigation R-100T; (ii) and (iii), an NML/Topcon Time Transfer System in single- or dual-frequency operation respectively; and (iv) and (v), as for (ii) and (iii) but with data processing using IGS precise ephemerides to calculate geometric ranges. Note the significant difference between modeled (L1 only) and directly measured (L1+L2) ionospheric delays evident in the last few days of the recorded data.



2 Processing Summary

Date	IGS Data	User Data	Orbit Type
2002-06-27	hers brus npld	BIPM	IGS Final
2002-06-28	hers brus npld	BIPM	IGS Final
2002-06-29	hers brus npld	BIPM	IGS Final

3 Computed Coordinates (ITRF2000)

All computed coordinates are based on the IGS realisation of the ITRF2000 reference frame, provided by the IGS cumulative solution. All the given ITRF2000 coordinates refer to a mean epoch of the site observation data. All coordinates refer to the Ground Mark.

3.1 Cartesian (ITRF2000)

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                    X(m)          Y(m)          Z(m)     ITRF2000@
      hers    4033470.156     23672.860   4924301.290  2002/06/28
      brus    4027893.789    307045.783   4919475.090  2002/06/28
      npld    3985500.333    -23625.491   4962941.673  2002/06/28
      BIPM    4203642.711    162935.309   4778194.035  2002/06/28
RMS   BIPM          0.011         0.010         0.010
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Figure 3: Extracts from the results of processing to obtain accurate antenna coordinates. Three days of dual-frequency carrier phase geodetic survey data were recorded by an NML Timing System in operation at BIPM, Paris, France, and processed using an online service provided by Geoscience Australia. The reported 1-σ coordinate uncertainty is approximately 1 cm.

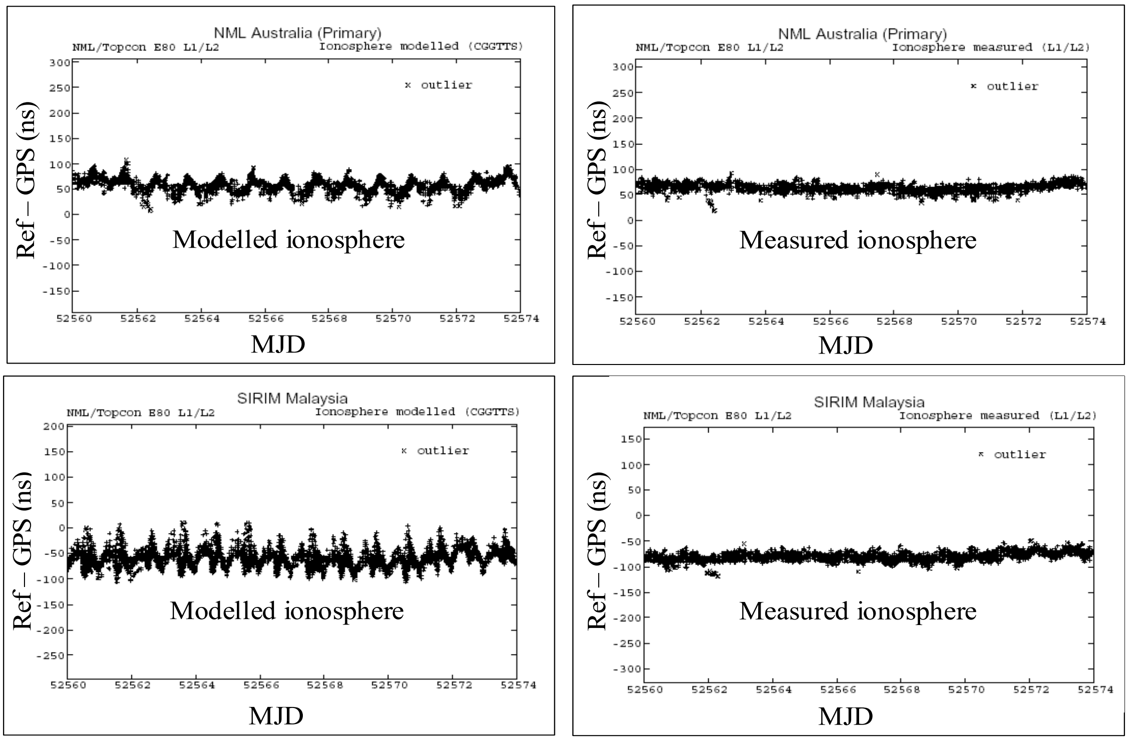

Figure 4: Demonstration of the substantial reduction in the diurnal variation of GPSCV time-transfer data afforded by direct, real-time ionospheric measurement, especially for equatorial regions.

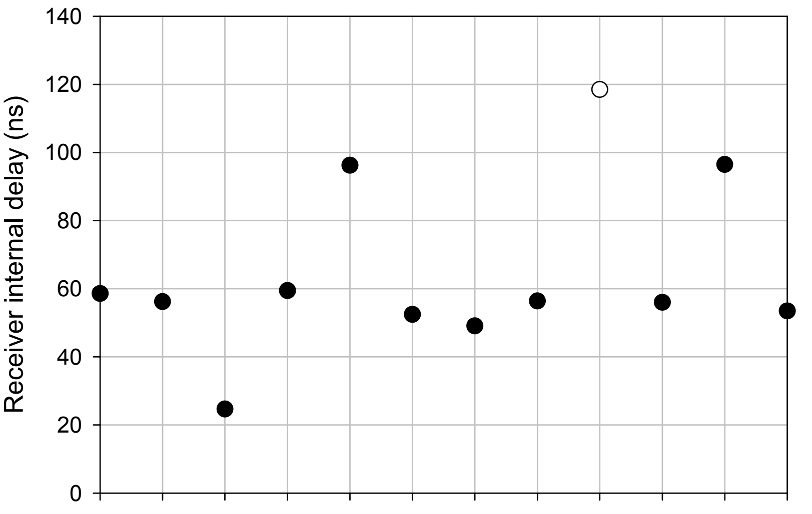

Figure 5: Results of the APMP round-robin intercomparison of GPS receivers. Values for the calibrated internal delay of Allan Osborne TTR6 (solid) and Austron (open) GPS receivers at participating APMP member institutes are shown, where the horizontal axis represents the chronological order of the intercomparison. A calibration was obtained for NML 446 by comparison with a receiver circulated by BIPM, and transferred by reanalyzing the data recorded at each participating institute together with reported values for antenna and cable delays.

Receiver	Type	Delay (ns)
NML 267	TTR6	58.6
TL	TTR6	56.2
NAO	TTR6	24.7
CRL	TTR6	59.4
NRLM	TTR6	96.2
KRISS	TTR6	52.5
SCL	TTR6	49.1
NML 267	TTR6	56.4
PSB	Austron	118.5
NPLI	TTR6	56.0
VMI	TTR6	96.5
NML 446	TTR6	53.5

Table 1: Results of the APMP round-robin intercomparison of GPS receivers (Figure 5).

NMI	Start MJD	Stop MJD	Tracks	Offset (ns)	RMS (ns)	Slope (ps/day)
NML 9/99	51391.9	51417.0	734	9.3	3.4	-9±13
TL	51480.0	51497.0	348	6.2	3.0	62±38
NAO	51534.3	51547.0	413	-25.3	3.4	-146±42
CRL	51551.4	51567.0	415	9.7	3.9	80±32
NRLM	51571.2	51595.0	707	32.2	5.5	70±21
KRISS	51626.1	51644.0	689	2.5	3.9	42±27
SCL	51648.3	51662.3	256	-5.9	3.9	74±61
NML 5/00	51704.0	51736.0	324	9.5	3.4	-35±15
NML 1/01	51890.1	51941.0	1338	11.6	3.5	38±6
PSB	51990.0	52015.0	371	-23.5	19.2	-307±132
NPLI	52061.5	52064.1	42	-8.0	4.1	1609±740
VMI	52100.4	52124.0	629	46.5	2.1	-40±12

Table 2: Results of comparisons between the NML travelling GPSCV receiver and those of participating laboratories. The mean offset (host–travelling) and the RMS deviation about the fitted line are given in ns, and the slope of the line in ps/day. The three comparisons conducted at NML were conducted between TTR6 serial numbers 446 (host) and 267 (travelling) receivers, and used to establish the calibrated internal delay for the latter.

NMI	Host receiver						Travelling receiver					
	Reported by NMI			Used by receiver			Reported by NMI			Used by receiver		
	INT	REF	CAB	INT	REF	CAB	INT	REF	CAB	INT	REF	CAB
NML 9/99	53.5	102.4	235	68	102	235	68	102.4	235	68	103	230
TL	50	51	229	50	51	229	58.6	51	235	68	51	235
NAO	50.	108	250	50	0	250	58.6	108	235	68	51	235
CRL	49.7	515.9	219.6	49.7	515.9	250	58.6	734.98	235	68	527.4	235
NRLM	64	89	250	64	89	250	58.6	0	235	68	0	235
KRISS	50	576	250	50	576	250	58.6	582	235	68	582	235
SCL	55	10	728	55	10	728	58.6	10	720	68	10	720
NML 5/00	53.5	79.1	235	68	79	235	68	79.9	235	68	79.6	235
NML 1/01	53.5	79.1	235	68	79	235	68	77.8	235	68	77.8	235
PSB	142	16	403	142	16	403	56.4	16	392	68	16	392
NPLI	64	53.8	250	64	0	250	56.4	20.8	235	68	16	235
VMI	50	38	250	50	23	250	56.4	68	235	68	68	235

Table 3: Values of delay parameters used in the APMP GPS receiver intercomparison.