Report to CCTF from the National Measurement Laboratory CSIRO Australia

May 2001

1. UTC(AUS) and TA(AUS)

The history of TA(AUS) and UTC(AUS) over the last three years is shown in figure 1, and the significant events affecting UTC(AUS) over that period are listed in table 1.

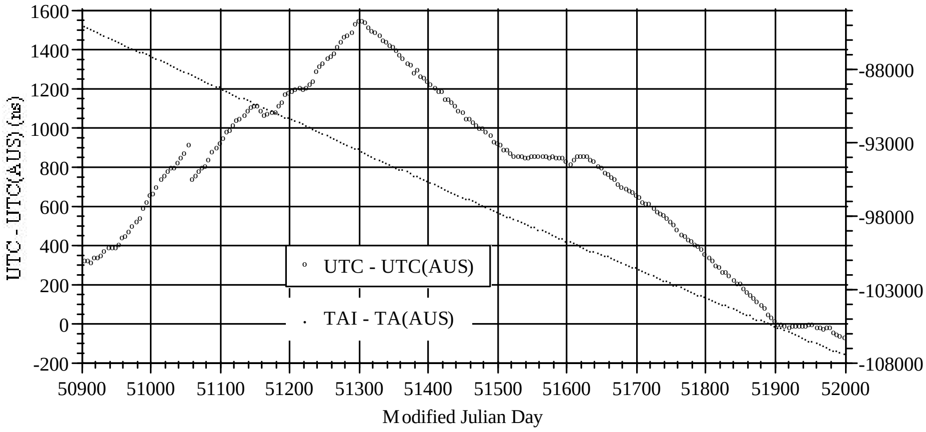

Figure 1: History of UTC(AUS) and TA(AUS) from May 1998 to March 2001.

MJD	Date	Event
51057	1 September 1998	Step due to phase divergence between the clocks NML1141 and Orr207 between the date they were synchronised and the date the output of NML1141 was designated UTC(AUS).
51162	15 December 1998	NML1141 failed and was replaced by NML299 as the representation of UTC(AUS).
51303	5 May 1999	A steer was applied to the frequency of Cs299 to cause UTC(AUS) to approach UTC at a rate of 5 ns per day.
51530	18 December 1999	A spontaneous frequency change in the output of Cs299 occurred.
51635	1 April 2000	A steer was applied to the frequency of Cs299 to re-establish the trend of UTC(AUS) towards UTC.
51878	30 November 2000	NML340 replaced NML299 as the representation of UTC(AUS), pre-empting the imminent failure of NML299.
51899	21 December 2000	A steer was applied to the frequency of Cs340 so that the frequency of UTC(AUS) approximates that of UTC with minimal offset between the two time-scales.

Table 1: Significant events affecting UTC(AUS).

2. ISO Quality System Accreditation

In November 1999 the NML Time and Frequency group was granted formal accreditation to ISO Guide 25 for its calibration and timekeeping activities. The international peer reviewers were Dr Shin-Ichi Ohshima from NRLM Japan, and Dr Rob Douglas from NRC Canada.

3. Timing facilities

NML maintains timing facilities in Melbourne and Perth, in addition to its primary facility in Sydney. The Melbourne and Perth remote facilities consist of a clock (Cs in Melbourne, Rb in Perth) maintained on-time with respect to UTC(AUS) using NML GPS common-view (GPSCV) time transfer hardware and software. The remote systems are monitored and maintained from Sydney via an Internet connection. The remote facilities provide GPS integrity monitoring, Network Time Protocol (NTP) and TV-Sync monitoring services. A sample daily GPS integrity monitoring report is attached as an appendix. The details of the NML common view time transfer systems are discussed in more detail in section 7 of this report.

The Melbourne system is located in a branch of NML where a full calibration service is available, whereas the Perth system is unmanned and provides NTP and monitoring services only. The installation of additional unmanned timing facilities in other state capital cities is planned for the next two years (figure 2).

Figure 2: Remote timing/NTP/GPS Integrity monitoring servers in Australia – existing (✰) and planned (❍)

4. Asia-Pacific Metrology Program (APMP) Activities

Under the auspices of the APMP Technical Committee for Time and Frequency, NML has been circulating an AOA TTR6 GPS receiver and associated hardware amongst Asia-Pacific NMIs for the purpose of comparing time-transfer receiver internal delays. The first round of the intercomparison took place between October 1999 and May 2000 and included the NMI's of Taiwan, Japan, Korea and Hong Kong. A second round including other Asia-Pacific NMI's is currently in progress. A report on the first round is available on the NML Time and Frequency FTP server: `ftp://time1.tip.csiro.au/pub/timedata/gps/APMP_data/GPS_Calibration/` .

5. Two Way Satellite Time Transfer (TWSTT)

NML presently maintains two TWSTT links, with details shown in Table 2. The primary purpose of the TWSTT experiments is to compare the performance of the GPS and TWSTT techniques over very long (NML-NIST) and trans-equatorial (NML-CRL) baselines, over a period of several years. Results of the NML-CRL experiment will be presented by the CRL representative.

NIST's Boulder laboratories are located at the base of the Rocky Mountains and do not have a view of any satellites that can be used for a TWSTT link with NML. However, NIST maintains the WWV timing broadcast station at Ft Collins, about 60 km north of Boulder. From Ft Collins, line of sight to Intelsat 701 is possible (although it is only three degrees above the horizon) and for this reason the NIST TWSTT C-Band Earth station used for the link to NML is located here. The short timing link to UTC(NIST, Boulder) is maintained by conventional GPS common view.

Data from the TWSTT link is presented in figure 3 where its difference from UTC(AUS)-UTC(NIST, Boulder) as given by Circular T has been plotted. The delays at both stations have not yet been calibrated and the offset indicated in figure 3 reflects this. The spike around MJD 51600 is due to an anomaly in the UTC(AUS) data given in Circular T and is an artefact. There is the suggestion of an oscillation with a period of about a year in the data but further data is required to verify this. In figure 4, UTC(AUS)-UTC(NIST) is plotted for both Circular T and the TWSTT link. The TWSTT exhibits more noise than the GPS link over time scales of several days, which may not be surprising since the TWSTT data is averaged over less than 30 minutes of transmission time per week, whereas the GPS Common-view data is quasi-continuous. The stability of the TWSTT link may also be affected by factors associated with the very low elevation of Intelsat 701 as viewed from Ft Collins.

The Telecommunications Laboratory (TL), Taiwan, plans to join the NML-NIST C-band link in 2001.

Link 1:

Tx/Rx Band	C-Band
Earth stations	NML, Sydney, Australia and NIST, Ft. Collins, USA
Satellite	INTELSAT 701, 180°E
Tx power	10 W
Antenna	4.6 m
Modem	MITREX
Timing reference	Std Perf. Cs (NML), High Perf. Cs (Ft. Collins)
Schedule	2 x 15 minute sessions per week
Regular operation began	July 1999

Link 2:

Tx/Rx Band	Ku-Band
Earth stations	NML, Sydney, Australia and CRL, Tokyo, Japan
Satellite	INTELSAT 702, 176°E
Tx power	4 W
Antenna	2.2 m
Modem	ATLANTIS
Timing reference	Std Perf. Cs (NML), High Perf. Cs (CRL)
Schedule	2 x 30 minute sessions per week
Regular operation began	March 1998

Table 2: TWSTT links between NML and NIST, Fort Collins, USA and NML and Communications Research Laboratory (CRL), Tokyo, Japan.

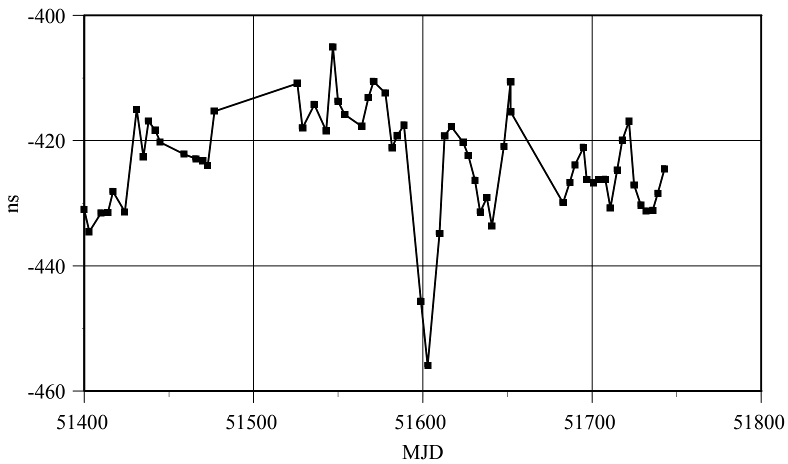

Figure 3: Difference between UTC(AUS) – UTC(NIST) as calculated from BIPM Circular T and UTC(AUS) – UTC(NIST) as determined from a TWSTT link between NML and NIST, Fort Collins.

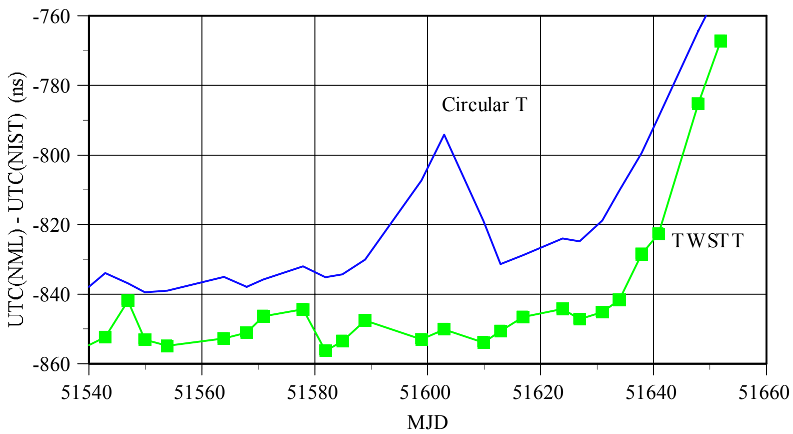

Figure 4: Comparison of UTC(AUS) – UTC(NIST) as calculated from BIPM Circular T and as determined from a TWSTT link between NML and NIST, Fort Collins. The TWSTT data has been offset for clarity.

6. Laser cooled $^{171}Yb^+$ Trapped Ion Frequency Standard

Work on the NML 12.6 GHz $^{171}Yb^+$ Trapped Ion Frequency Standard has continued slowly, as permitted by the other responsibilities of the Time and Frequency group.

Operation of the $^{171}Yb^+$ standard in buffer gas-cooled mode has already been reported [1], and since the 1999 CCTF meeting, work on this project has focussed on the determining the uncertainty budget for the standard under conditions where the ion cloud is laser-cooled to sub-Kelvin temperatures.

Accurate realisation of the frequency of the 12.6 GHz clock transition in the laser-cooled regime requires that the ions remain sufficiently cold during Ramsey interrogation periods of 10 s or longer so that motional second-order Doppler shifts remain small. The cooling light must be blocked during the interrogation to avoid dynamic Stark shifts. During this time the ions are subject to RF heating from the trapping fields.

We have carried out comprehensive measurements of the effective temperature corresponding to kinetic energy of secular motion, resolved along the symmetry axis of the linear trap (figure 5, solid points) and transverse to this axis (figure 5, open points) [2]. There is evidence from other data that the apparent transverse temperature excess in this data set is an instrumental artefact, and we therefore deduce that the cold ion cloud is in thermal equilibrium. The corresponding fractional second-order Doppler shift remains at or below 10^{-15} for at least 15 s in the absence of laser cooling. The equivalent shift for driven micromotion is readily calculated.

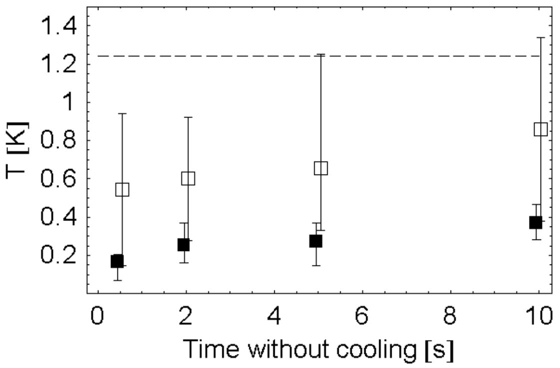

Figure 5: Effective temperature of secular motion as a function of time without laser cooling (see text). The dashed line corresponds to a fractional second-order Doppler shift of 10^{-15}.

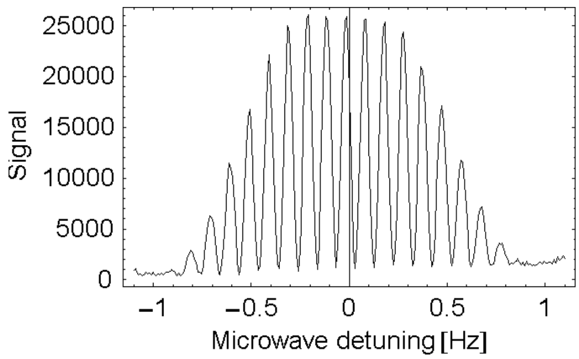

Figure 6: Ramsey fringes recorded for a laser-cooled cloud of ~10^4 $^{171}Yb^+$ ions with a 10 s Ramsey time [3]. A constant background has been subtracted.

The laser-cooled $^{171}Yb^+$ frequency standard should therefore exhibit performance comparable to a caesium fountain. The projected short-term stability for a 10 s Ramsey time is equivalent to the buffer-gas cooled standard ($\sigma_y(\tau) = 5\times10^{-14}\ \tau^{-1/2}$ [1]) and microwave spectroscopy has already been demonstrated under these conditions (figure 6, [3]). Other systematic effects (particularly due to the homogeneity and stability of the magnetic field, the uniformity of the microwave interrogation field, and excess micromotion) have been controlled and characterised in other frequency standards to an uncertainty of parts in 10^{15} or better. We see no insurmountable obstacle to realising a combined absolute uncertainty at or below 4×10^{-15} in the present first-generation apparatus, with the prospect of further improvement through redesign. Work is under way to demonstrate the projected stability and accuracy of the laser-cooled standard.

7. Developing Better GPS Time Transfer Systems

There is a need within Australia for systems capable of high-integrity time and frequency transfer and which can be operated, monitored and maintained remotely. The initial motivation for developing such systems at NML was to provide a "turnkey" solution for customers who wished to maintain high-accuracy, high-integrity frequency and time traceability from a Cs or Rb frequency standard to NML without the inconvenience of shipping the standard to NML for calibration.

The NML GPSCV Timing Systems in their most basic form consist of an Intel-based PC running the Linux operating system, a commercially available GPS receiver board and antenna, and a commercially available counter-timer. NML's philosophy was to use relatively generic hardware, and to make the software as independent as possible of the hardware. This allows the system to be flexible, and capable of extensive future development as customer demand changes and hardware technology and availability evolves. Because the system is controlled by a Linux-based computer, it can perform many different functions in addition to GPSCV time transfer, and can be controlled and monitored remotely via the Internet or a telephone line.

The NML software implements the full CGTTS data processing protocol and output file formats, for both single- and dual-frequency receivers [4].

The uncompromised remote operability and maintainability has proven especially useful in remote installations both within and outside Australia, and they can provide high integrity, real-time frequency and timing services in un-staffed environments. In addition, they have been found suitable for use as either backup or primary time transfer systems in NMI timing laboratories, and are presently installed at seven Asia-Pacific NMIs. Extended versions of these systems have also proved to be useful and reliable as remotely-operable Network Time Protocol servers, TV-Sync monitoring stations, and GPS integrity monitoring stations. Three such systems are currently operating within Australia.

The NML GPSCV Timing Systems were originally based on the Motorola VP Oncore GPS receiver. This receiver has not been available since the end of 1999. The only suitable replacement receivers known to us are manufactured by the Topcon Positioning Systems company (who took over the Javad company). We have modified and extended the NML software to operate with the Topcon Euro-80 L1/L2 dual frequency GPS receiver, and the performance data presented in this report are from that receiver.

Figure 7 shows data extracted directly from CGTTS format data files over a period of 20 days. For comparison, GPS data from a 3S Navigation R-100T receiver is also shown. The single frequency GPS data is from REF-GPS (column 10 in the CGTTS data format); this data includes the modelled ionospheric correction (MDIO, column 16), calculated according to broadcast parameters using the algorithm presented in the GPS Interface Control Document (ICD). The third trace from the top on Figure 1 has the modelled ionospheric correction removed and the measured correction (MSIO, column 18) included;
viz. (REF – GPS) + MDIO – MSIO, in the terminology of the CGTTS data format.

IGS precise ephemerides were used to calculate the CGTTS data files from which the lowest two traces of figure 7 were plotted, using modelled and measured ionospheric corrections respectively. These traces show more clearly the improved performance offered by the L1/L2 ionospheric measurement capability, especially during periods of apparently intense solar activity around MJD52038. Figure 8 shows the same data plotted over a two day period.

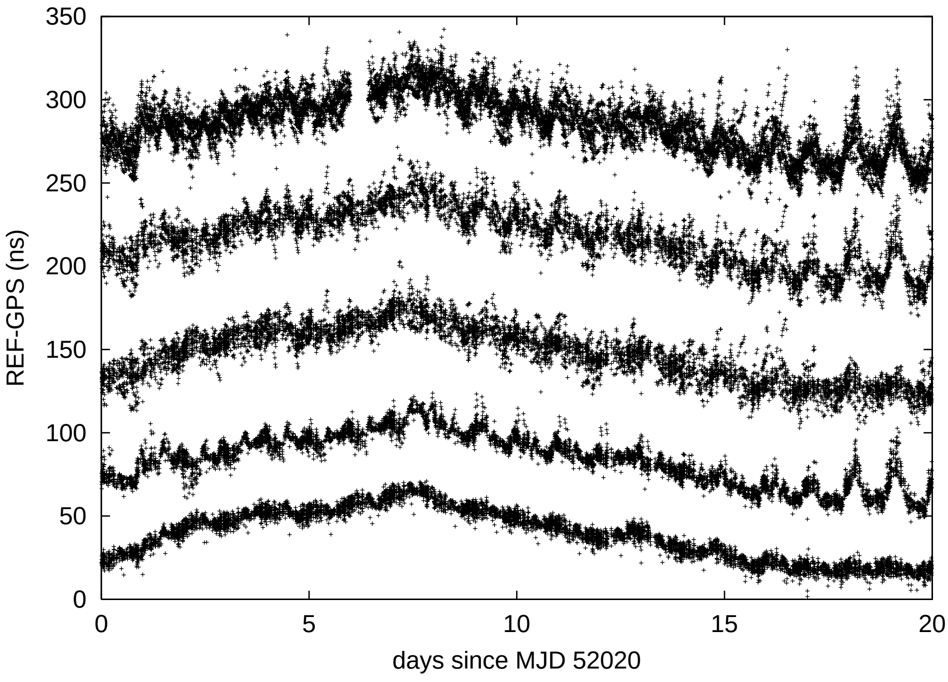

Figure 7:
REF–GPS data recorded at NML, taken from CGTTS data files (see text). From the top, the traces are:

1) *REF–GPS from a 3S Navigation R100T GPS receiver*
2) *REF–GPS from an NML/Topcon dual frequency GPSCV Timing System using broadcast ephemerides and modelled ionospheric corrections*
3) *As for trace 2, but using measured L1/L2 ionospheric corrections*
4) *As for trace 2, but using IGS precise ephemerides*
5) *As for trace 2, but using IGS precise ephemerides and measured L1/L2 ionospheric corrections. The traces have been vertically offset to aid comparison.*

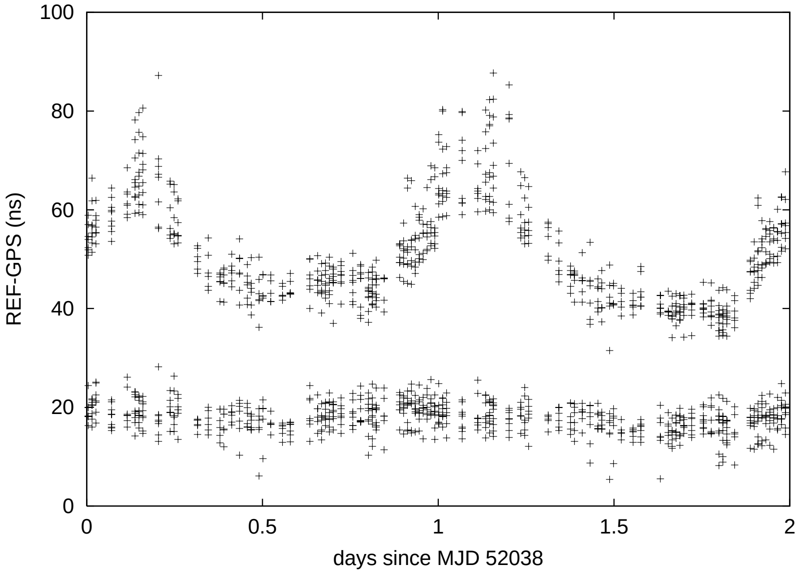

Figure 8: Data from traces 4 and 5 of figure 7 plotted over a two day period.

Since early 2000, NML has used Motorola VP Oncore-based CVGPS time transfer systems very successfully as remote Network Time Protocol (NTP) servers. These NTP servers consist of the basic NML Timing System, together with a Rb or Cs clock which can be controlled via a serial connection to the Linux PC. The epoch of the 1 pps output of the clock is maintained with respect to UTC(AUS) using the standard GPSCV time transfer technique. The 1 pps signal is monitored from the Linux PC via a simple circuit which uses the pulse to trigger the sending of an ASCII carriage return character over a serial link. The arrival of this character at the PC serial port is used as a precise timing reference by an NML-developed driver installed in the standard NTP software suite on the Linux PC. A second GPS receiver is used to generate a timestamp for the 1 pps pulses, which is received by a second custom driver. NML operates these systems in Sydney, Melbourne and Perth, and the installation of further systems in other cities is planned.

References

[1] P. T. H. Fisk, M. J. Sellars, M. A. Lawn, and C. Coles, *IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control* **44** 344–354 (1997).

[2] R. B. Warrington, P. T. H. Fisk, M. J. Wouters, and M. A. Lawn, in preparation (2001).

[3] R. B. Warrington, P. T. H. Fisk, M. J. Wouters, M. A. Lawn and C. Coles, *Proc. 1999 EFTF/IEEE FCS*, IEEE **99CH36313** 125–128 (1999).

[4] D.W. Allan and C. Thomas, *Metrologia* **31** 69-79 (1994)

Appendix: Sample GPS integrity monitoring report generated by an NML CVGPS Timing System.

GPS Space Vehicle Time Integrity for MJD 52045

As viewed from the CSIRO National Measurement Laboratory, Sydney, Australia
Latitude -33.7828269 degrees, longitude 151.1516104 degrees, height 99.2 metres

A	B	C	D	E	F	G	H	I	J	K
PRN	Block no.	Start	End	Measure-ments	UTC(AUS) -GPS_{SV} (ns)	UTC(AUS) -SV (ns)	Std.Dev. (ns)	Outliers > 4 σ	Outliers > 500 ns	Health
1	1	00:00	03:46	13,618	149	-177,818	6	1	0	0
1	2	20:42	23:59	11,836	152	-177,937	3	0	0	0
2	1	02:33	06:41	14,866	160	15,124	19	0	0	0
2	2	06:50	09:35	9,906	145	15,182	15	0	0	0
3	1	00:33	03:37	11,054	152	-29,357	9	1	0	0
3	2	15:19	19:53	16,462	145	-29,568	17	0	0	0
4	1	06:50	11:36	17,193	141	-697,119	25	1	0	0
5	1	08:08	13:59	21,066	144	-297,922	10	0	0	0
6	1	10:14	16:48	23,657	151	962	4	20	0	0
7	1	03:59	06:41	9,749	162	-569,127	23	0	0	0
7	2	06:50	10:07	11,819	147	-569,037	28	0	0	0
8	1	00:40	06:41	21,656	161	-227,581	244	0	0	0
9	1	06:50	11:36	17,189	148	45,218	6	1	0	0
9	2	16:33	18:55	8,521	151	45,267	7	0	0	0
10	1	02:37	04:51	8,048	168	-3,792	4	2	0	0
10	2	09:54	14:52	17,845	147	-3,830	3	23	0	0
11	1	04:30	06:41	7,826	162	-1,964	3	9	0	0
11	2	18:44	23:37	17,569	154	-1,981	4	5	0	0
12	-									
13	1	00:00	05:04	18,257	159	1,956	3	0	0	0
13	2	22:34	23:59	5,120	154	1,971	4	1	0	0
14	1	16:05	22:22	22,630	154	107,899	18	0	0	0
15	1	12:26	19:40	25,991	147	-33,891	31	0	0	0
16	-									
17	1	11:33	18:48	26,126	156	-22,836	43	0	0	0
18	1	13:05	19:48	24,160	147	88,358	34	0	0	0
19	-									
20	1	00:00	02:07	7,669	153	71,017	4	1	0	0
20	2	20:10	23:59	13,760	152	71,189	13	0	0	0
21	1	14:37	21:42	25,496	149	-2,984	5	56	0	0
22	1	00:00	02:10	7,826	159	-587,265	4	1	0	0
22	2	13:54	16:33	9,531	143	-587,364	5	1	0	0
22	3	21:14	23:59	9,904	166	-587,383	6	0	0	0
23	1	12:51	19:13	22,907	142	-12,885	12	0	0	0

24	1	07:35	13:20	20,689	157	-50,687	19	0	0	0
25	1	18:28	23:56	19,673	151	-13,500	3	32	0	0
26	1	04:36	06:41	7,508	160	-476,118	37	0	0	0
26	2	06:50	08:28	5,937	151	-476,235	27	1	0	0
26	3	12:57	16:55	14,270	145	-476,635	62	0	0	0
27	1	00:00	06:41	24,089	162	-20,468	12	1	0	0
28	1	00:00	04:42	16,939	155	-6,405	10	1	0	0
29	1	16:23	22:47	23,005	148	-548,899	67	0	0	0
30	1	09:33	14:57	19,430	138	20,044	7	0	0	0
31	1	00:59	05:13	15,205	162	-43,963	5	5	0	0
31	2	16:51	20:29	13,081	141	-44,060	8	0	0	0
32	-									
33	-									
34	-									
35	-									
36	-									
37	-									
38	-									
39	-									
40	-									

A: Space vehicle identification number.
B: The period when the satellite was in view. Each of these measurement blocks is a series of measurements longer than 60 minutes, containing no breaks of more than 60 seconds.
C: Time at the start of the block (UTC).
D: Time at the end of the block (UTC).
E: Number of 1 second pseudorange measurements in the block.
F: Average value of UTC(AUS) minus GPS satellite time during the block (A constant offset over the course of a day is to be expected).
G: Average value of UTC(AUS) minus space vehicle time during the block, in nanoseconds.
H: Standard deviation of G during the block, in nanoseconds.
I: Number of measurements more than 4 standard deviations from the average.
J: Number of measurements more than 500 ns from the average.
K: Number of non-zero health flags in the block.