First Results of GPS Time Transfer to Australia

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A GPS time transfer unit built by NBS under contract to JPL was installed at Tidbinbilla Deep Space Communications Complex of the DSN in June 1983. It has been used to estimate the relationship to UTC(USNO MC) of the Tidbinbilla frequency and time system TID(FTS) based on a hydrogen maser, and thence to estimate the performance of the Australian free-running time scale UTC(AUS). Data from the first three months has been analyzed three ways: by two-hop "common view" using JPL as intermediary; by "long-arc" interpolation of measurements against space vehicle clocks; and by "long-arc" interpolation of GPS-Time results. Residuals from a single quadratic fit through three months of UTC(USNO MC) – TID(FTS) results were white noise with standard error 15 ns, and a flying clock measurement gave 70 ns agreement. A straight line fit through results UTC(USNO MC) – UTC(AUS) gave 90 ns standard error and 120 ns agreement. It is proposed to use the GPS measurements to steer UTC(AUS) to UTC(BIH), and to rename the existing time scale TA(AUS).

I. Introduction

A Global Positioning System (GPS) Time Transfer Unit (TTU) built by U.S. National Bureau of Standards (NBS) for the DSN was installed at Deep Space Communications Complex (DSCC) 42/43 at Tidbinbilla (TID) in late June 1983. It was turned on in July and has operated correctly from that moment. Its principal function of interest here is to monitor the performance of the Tidbinbilla Frequency and Time System (TID(FTS)), which was derived from a SAO Model VLG11 hydrogen maser P14 during the period to November 1983. The basic results recorded are the time intervals between TID(FTS) 1 pps and the timing marks broadcast from the clocks on board each GPS space vehicle (SV), corrected in real time for propagation delay calculated from the on-board ephemeris transmitted by each SV and an assumed position for the antenna:

$$\lambda = 148°58'48''2018 \text{ E}$$

$$\phi = 35°24'8''0444 \text{ S}$$

$$h = 665.54 \text{ m}$$

Also available is the time comparison between TID(FTS) and the GPS master clock (GPS TIME) in the GPS Control Segment (Ref. 1). Generally two passes from each of space vehicles 5, 6, 8, and 9 are observed each day, of which only the higher altitude passes are used in this analysis.

Similar results are obtained on each SV at the US Naval Observatory (USNO), referred to their Master Clock (UTC(USNO MC)), although at different times in the day, and made available through the bulletin Series 4: Daily Phase Values, and otherwise. Time transfer between UTC (USNO MC) and TID(FTS) is obtained by linear interpolation to the time of a Tidbinbilla observation between two adjacent reported USNO observations, usually but not always one sidereal day apart. In this paper, data gaps up to two days are tolerated, and only linear interpolations are employed; hence it is tacitly assumed that on-board clock behaviour is linear over a day or two and that receiving antennae locations and broadcast orbital parameters are accurate. Because of the appreciable interpolating factors, this method is here designated "long arc" and is applied to results obtained both from SV observations and GPS TIME results.

The "common view" method in which both stations take measurements simultaneously (Refs. 2 and 3) is impossible between Tidbinbilla and USNO and difficult between Tidbinbilla and Jet Propulsion Laboratory (JPL). Nevertheless a two-hop quasi-"common-view" experiment has been attempted, with a GPS TTU at JPL taking nearly simultaneous observations with Tidbinbilla on the one hand, and nearly simultaneous observations with USNO on the other. The effectiveness of the time transfer then depends on the behaviour of the JPL Frequency and Time System between the two sets of observations which may be several hours apart.

Since four satellites were available, and more can be expected, the opportunity exists for averaging. This has been done by interpolating linearly to 0^h UTC between adjacent time transfer results from each satellite prior to taking the mean. This process yields a "consolidated" result.

II. The Tidbinbilla GPS System

A. Equipment

The GPS equipment installation at the Canberra Deep Space Communication Complex (CDSCC), Tidbinbilla, is depicted in Fig. 1. All of the equipment with the exception of the antenna unit is mounted in a short rack adjacent to the CDSCC frequency and timing system (FTS) monitor panel in the operations building (Fig. 2). The antenna unit, which also includes a low noise amplifier and mixer, is a sealed enclosure located on the roof of the operations building (Fig. 3).

The antenna position was obtained by carrying out a traverse from the surveyed ground monument position beneath the DSS 42 34-metre antenna. A receiver offset of 272 nanoseconds was inserted in the GPS software to correct for the delay due to cable length between antenna unit and receiver.

A 5 MHz signal is provided from the FTS as a reference frequency from which is derived the receiver 100 MHz to supply the first I.F. mixer in the antenna unit. D.C. power is also run through the 100 MHz coax cable, avoiding the requirement to provide a separate power cable. A 1 PPS signal is also connected from the FTS to provide the CDSCC clock reference to the system.

A modem phone is connected to an RS 232 port of the microprocessor to allow data acquired and stored by the system to be transmitted periodically by telephone to JPL, usually once a week. Data from a remote receiver may also be printed out locally using this modem link.

B. Operation of GPS Receiver

The GPS receiving system is capable of running in an automatic mode, once all relevant parameters have been entered. In this mode, the system will acquire chosen space vehicles, lock onto the downlink, and accumulate relevant data. The system is normally operated in the automatic mode at DSS 43.

The software/operator interface consists of a "user friendly," menu-driven parameter selection matrix, arranged in the form of one main menu and a number of submenus.

In order to bring the system up to a functioning condition, it is necessary to perform a "cold start" operation. This consists of instructing the system to acquire an almanac from a satellite when such a vehicle is within reception range (usually above horizon). It is also necessary to set the system's internal UTC clock by responding to the system prompts. Under normal operating conditions, a battery back-up supply maintains the system's RAM such that a cold start is not necessary even in the event of a power failure.

The system software provides an aid to the selection of suitable satellites for tracking purposes. If selected, the system will print a graph of elevation and azimuth versus time for up to five vehicles, dependent, of course, on the system's knowledge of its present location. This parameter may be entered by calling up the NEW RECEIVER COORDINATES feature on the display menu.

Once suitable satellites to track have been selected, appropriate track times may be entered, derived from the aforementioned graph. The facility exists to cause the system to decrement the track start times by 4 minutes per day to account for the fact that the satellites are in sidereal orbits. The satellite may then be tracked in the same position in the sky each day.

The system may be commanded to perform position location calculations by one of two methods. The first method requires that four satellites be in view so that data of sufficient precision may be obtained for the navigation solution. The second method requires that the system lock sequentially onto four satellites every two minutes. This second method produces a solution in a shorter time than the former and has the advantage of eliminating much of the short term noise in the local clock system.

The GPS measurement computation is performed by calculating a pseudorange value from system counter measurements and then computing the slant range, relativistic and ionospheric corrections based on data obtained from the satellite ephemeris. These corrections, along with the local receiver delay, are subtracted from the pseudorange estimate to obtain the local clock minus satellite clock value. The satellite clock correction, transmitted from the vehicle is then added to this value to produce a figure for local clock minus GPS clock.

III. Space Vehicle and GPS Times

The results produced by Tidbinbilla's GPS TTU are, for each SV(i), numbers in the form TID(FTS) – SV(i) and TID(FTS) – GPS TIME via SV(i). The corresponding numbers disseminated by USNO are UTC(USNO MC) – SV(i) and UTC (USNO MC) – GPS TIME via SV(i). It has been found that the "raw" results TID-SV and USNO-SV are adequately modelled by quadratic curves over the interval MJD 5528-5618 for SV(5) and SV(9), while cubic or higher-order fits would be required for SV(6) and SV(8). The parameters of the quadratics are given in Table 1 in the form:

$$\text{TID(FTS)} - \text{SV}(i) = a(i) + b(i) \times (t - \bar{t}) + c(i) \times (t - \bar{t})^2 \qquad (1)$$

and similarly for UTC(USNO MC) - SV(i), where $a(i)$ is the offset at the mean time $\bar{t}$, $b(i)$ is the rate at $\bar{t}$ and $c(i)$ is half the drift rate. The standard errors of residuals $\sigma(i)$ are also tabled, and the residuals are displayed in Figs. 4 and 5. Both graphs have many features in common, demonstrating that vagaries in on-board clock behaviour are readily detectable.

Several rate changes were observed to occur in GPS time in the interval considered, so the results were broken into four segments and straight lines fitted through each as shown in Tables 2 and 3. The residuals are displayed all together in Figs. 6 and 7, where it can be seen that results are rather better at USNO than at Tidbinbilla which is possibly a consequence of efforts made at the GPS master station to follow USNO time.

IV. Long-Arc Time Transfer to USNO

Time transfer from USNO to Tidbinbilla was achieved by linearly interpolating between successive daily results UTC (USNO MC) – SV(i), and subtracting the observed value of TID(FTS) – SV(i) from it. It was felt that it was better to use the USNO results to interpolate on since its time scale is the reference being accessed and is therefore to be considered definitive for these purposes. Linear interpolation was adequate and in fact desirable since the effects of drift rate over one or two days are swamped in the random noise. The "consolidated" result is shown in Fig. 8, on which is also shown the value

$$\text{UTC(USNO MC)} - \text{TID(FTS)} = -11.030\ \mu\text{s}$$

by USNO/Bendix flying clock on 1 October 1983.

Quadratic curves in the same form as Eq. (1) were fitted to the outcomes using each space vehicle separately. Their parameters are given in Table 4, and the residuals therefrom are shown in Fig. 9. Residuals from the "consolidated" time transfer are shown in Fig. 10, and the Allan variances of these residuals are displayed in Fig. 11 in which the slope is close to -1, indicating that the residuals after removal of the quadratic are very nearly random uncorrelated "white" phase noise.

Almost identical results are obtained when transfer is effected via GPS TIME instead of SV TIME. Table 4 contains their quadratic parameters, Fig. 12 shows their consolidated Allan variances, Fig. 13 the individual residuals and Fig. 14 the consolidated residuals.

From this analysis, the drift rate of the Tidbinbilla hydrogen maser with respect to UTC(USNO MC) is +4 parts in 10^{15} per day, and is undoubtedly now well measured: The drift rate itself has not changed during three months.

V. Common View Measurements

The results given above show quite clearly that the GPS receivers can detect anomalies in the on-board clocks and in GPS TIME as small as 10 ns or less, so simultaneous observations should remove their effects. The geographical locations of Tidbinbilla and USNO make "common view" observations impossible, so a two-hop scheme is necessary. In this, the GPS TTU at JPL's Goldstone Radar Net (GRN) has been taking measurements at the same time as USNO (to within ten minutes) and also at the same time as Tidbinbilla (to within one minute) each day. The hydrogen maser based timing system at GRN has a rate of about 20 ns/day but is assumed here to be error-free in relating the two sets of measurements. Then,

$$\text{UTC(USNO MC)} - \text{TID(FTS)} = [\text{UTC(USNO MC)} - \text{JPL}] - [\text{TID(FTS)} - \text{JPL}] \tag{2}$$

Results from GPS TIME averaged over all space vehicles are shown in Fig. 15, and residuals from the quadratic fit whose parameters are given in Table 4 are in Fig. 16. Figure 17 shows the results in the vicinity of the 1 October flying clock measurement, while Fig. 18 gives Allan variances after the quadratic curve has been removed.

Figure 19 copies Figs. 10, 14 and 16 to show the residuals by each of the three methods on one graph. It can be seen that the "common view" results have some spikes not visible in the other results, but that otherwise the results are quite similar. It is noteworthy that the statistics given in Table 4 for "long-arc" using SV TIME and using GPS TIME are very similar, and differ by about 170 ns in offset and 2 ns/day in rate from the "common view" results whose standard error is also somewhat larger. It is therefore evident that the greater atmospheric effects caused by the "common view" method in this case outweigh the clock modelling errors of the "long arc" method.

VI. Transfer to UTC(AUS)

The free-running time scale UTC(AUS) is calculated from TV comparisons between caesium standards and hydrogen masers located mainly in Canberra, Sydney and Melbourne (Refs. 4 and 5). The clocks contributing to UTC(AUS) in the three month period under consideration are summarised in Table 5. Until the GPS receiver was put in to use at Tidbinbilla, the only regular means of comparing UTC(AUS) with adequate precision to the outside world was by flying clock trips every three or four months organised by USNO and Bendix Corporation. It is now possible, however, to measure the relationship on a daily basis, using TID(FTS) as the intermediary.

The results UTC(AUS) – TID(FTS) as published in NATMAP's Bulletin E during July-October are shown in Fig. 20. Combining these with UTC(USNO MC) – TID(FTS) as in Fig. 8 gives UTC(USNO MC) – UTC(AUS) shown in Fig. 21. Residuals from a straight line fit (see Table 4) are shown in Fig. 22 and their Allan variances in Fig. 23. It is immediately seen that the standard errors are almost an order of magnitude greater, which is directly attributable to TV noise. The flying clock trip error is 120 ns of which a substantial proportion can be attributed to the flying clocks themselves.

There is no doubt that, for as long as the GPS TTU remains at Tidbinbilla, a regular, reliable and accurate avenue is available for comparing clocks in Eastern Australia to clocks and time scales overseas. Conversely, it is now possible for 16 or more Southern Hemisphere clocks to be used in the computation of International Atomic Time (TAI) if so desired.

VII. Use of Results to Steer UTC(AUS)

Time scales such as UTC(AUS), UTC(BIH) and UTC(USNO) are calculated in batch mode after-the-event; for example, UTC(AUS) is calculated monthly about a fortnight in arrears. It is thus feasible to accommodate the delays in gathering GPS data and reducing them to a common time such as 0^h UTC in order to include it in the time scale algorithm. This can be done in such a way that the time scale generally follows the external clock or scale to which the GPS measurements are referred, yet continues virtually uninterrupted if the GPS results are unavailable.

Let the time shown by clock i be denoted x_i at a given time, and let the measurement against the local TV (corrected for propagation delay) be l_i:

$$l_i = x_i - \text{TV}, \qquad i = 1, 2, \ldots, n \tag{3}$$

It is desired to calculate a time scale X, e.g., $X = \text{UTC(AUS)}$, which appears in the form of a set of results z_i:

$$\begin{aligned} z_i &= X - x_i, \qquad i = 1, 2, \ldots, n. \\ z_o &= X - \text{TV} \end{aligned} \tag{4}$$

taking into account weights p_i for each clock according to some prearranged criteria. This is achieved by invoking the fundamental time scale equation (Ref. 6):

$$\sum_{i=1}^{n} p_i (z_i - \hat{z}_i) = 0 \tag{5}$$

where $\hat{z}_i$ is an unbiassed prediction of UTC(AUS) - x_i at the time of observation (Ref. 7). There are n observations and one condition available to solve for the $n + 1$ unknowns z_0, $z_1, z_2, \ldots, z_n$.

Now suppose that an external observation l_T is available on one of the clocks $x_T(T \epsilon_i)$ against the reference time scale R, e.g., R = UTC(USNO MC):

$$l_T = R - x_T \tag{6}$$

and impose the steering condition:

$$X = R \tag{7}$$

i.e., UTC(AUS) = UTC(USNO MC) at the time of measurement. The full set of equations to be solved can then be put into the form of observation equations with a condition, from Eqs. (6), (3) and (5) respectively:

$$\begin{aligned} l_T &= z_T, & T \epsilon i \\ l_i &= z_o - z_i, & i = 1, 2, \ldots, n \\ \sum_{i=1}^{n} p_i(z_i - \hat{z}_i) &= 0 \end{aligned} \tag{8}$$

which can be treated by standard least squares methods; a weight p_T should be assigned judiciously to the external direct observation l_T. This formulation can be readily extended to cater for the hypothetical situation in which several GPS units, or indeed any other international time transfer systems, were operating in Australia.

When this suggestion has been investigated and implemented, UTC(AUS) will be truly a coordinated scale of Universal Time. Removal of the direct external observation(s) l_T would restore it to its current position as a true free-running time scale, more appropriately designated perhaps as TA(AUS) yet regularly monitored against TAI. It is proposed to run both solutions once certain prediction and weighting biases in the UTC(AUS) algorithm have been removed.

VIII. Conclusion

It has been demonstrated that the GPS TTU at Tidbinbilla DSCC can achieve time transfer half way around the world with 20 nanosecond precision over extended periods and with accuracy inside the measurement capability of flying clocks. Little degradation occurs by employing the "long-arc" method rather than the "common view" method because "common view" requires low observing altitudes over these distances, and use of USNO GPS TIME values is almost as good as USNO SV values, besides being easier to obtain.

The first practical application of the method has been the determination of the drift rate of Tidbinbilla's hydrogen maser as 4 parts in 10^{15} per day.

Because the user data processing has proved to be very straightforward, it is highly feasible to include the results in the computation of UTC(AUS) and indeed to steer this time scale to UTC(USNO MC) or to UTC(BIH). It is also now possible for a wider community to use Australian clocks for scientific purposes. We hope that other Southeast Asian and Pacific countries will be encouraged by our results to examine the method very closely.

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Table 1. Quadratic fits to observations on satellite clocks

Observation	Offset (a), μs	Rate (b), $\mu s/d$	Drift/2 (c), $\mu s/d/d$	Average time ($\bar{t}$), MJD	Standard error (σ), μs
TID(FTS-SV(5)	188.236	0.213022	0.00009463	5571.18	0.01
TID(FTS)-SV(9)	15.809	0.075300	0.00022562	5572.31	0.01
UTC(USNOMC)-SV(5)	180.642	0.144689	-0.00009541	5575.53	0.05
UTC(USNOMC)-SV(9)	7.562	0.007514	0.00004740	5575.20	0.03

Table 2. Straight line fits to TID(FTS) – GPS TIME

SV No.	Offset (a), μs	Rate (b), $\mu s/d$	Average time ($\bar{t}$), MJD	Standard error (σ), μs	Smoothed	Between
5	5.861	0.08233	5530.75	0.02	5528	5532
6	5.874	0.05275	5530.78	0.03	5528	5532
8	5.887	0.07441	5531.21	0.03	5528	5532
9	5.812	0.07190	5530.86	0.02	5528	5532
5	6.282	0.05981	5537.74	0.04	5532	5542
6	6.296	0.06118	5537.77	0.02	5532	5542
8	6.293	0.06123	5537.69	0.02	5532	5542
9	6.287	0.06314	5538.17	0.02	5532	5542
5	7.269	0.08851	5549.99	0.01	5542	5556
6	7.280	0.09221	5550.01	0.02	5542	5556
8	7.265	0.09207	5549.66	0.02	5542	5556
9	7.221	0.08997	5549.80	0.03	5542	5556
5	8.979	0.06995	5573.14	0.04	5556	5589
6	9.010	0.07002	5573.16	0.02	5556	5589
8	9.017	0.09669	5572.96	0.02	5556	5589
9	8.962	0.07134	5573.24	0.03	5556	5589
5	10.339	0.06487	5592.08	0.03	5589	5594
6	10.368	0.07126	5592.11	0.01	5589	5594
8	10.377	0.06552	5592.04	0.02	5589	5594
9	10.327	0.06830	5592.19	0.02	5589	5594
5	11.060	0.14007	5598.07	0.03	5594	5601
6	11.094	0.13991	5598.09	0.03	5594	5601
8	11.102	0.14669	5598.02	0.03	5594	5601
9	11.047	0.14017	5598.17	0.03	5594	5601
5	11.763	0.08500	5604.35	0.02	5601	5607
6	11.806	0.08724	5604.37	0.02	5601	5607
8	11.846	0.09814	5604.44	0.02	5601	5607
9	11.754	0.09100	5604.45	0.02	5601	5607
5	12.401	0.07943	5612.08	0.02	5607	5618
6	12.431	0.07593	5612.25	0.02	5607	5618
8	12.455	0.07508	5612.18	0.02	5607	5618
9	12.384	0.07606	5612.33	0.01	5607	5618

Table 3. Straight line fits to UTC(USNOMC) – GPS TIME

SV No.	Offset (a), μs	Rate (b), $\mu s/d$	Average time ($\bar{t}$), MJD	Standard error (σ), μs	Smoothed	Between
5	0.054	0.02183	5529.91	0.02	5528	5532
6	0.075	0.01957	5530.83	0.01	5528	5532
8	0.078	0.02276	5531.24	0.02	5528	5532
9	0.054	0.02202	5529.99	0.01	5528	5532
5	0.115	0.00188	5537.00	0.01	5532	5542
6	0.127	0.00565	5537.76	0.01	5532	5542
8	0.108	0.00003	5537.70	0.03	5532	5542
9	0.114	0.00349	5536.98	0.01	5532	5542
5	0.360	0.03048	5549.50	0.01	5542	5556
6	0.388	0.02952	5550.24	0.01	5542	5556
8	0.392	0.03226	5549.92	0.02	5542	5556
9	0.394	0.03135	5549.98	0.02	5542	5556
5	0.630	0.00270	5582.29	0.01	5556	5589
6	0.610	0.00207	5582.30	0.02	5556	5589
8	0.619	0.00197	5582.36	0.02	5556	5589
9	0.619	0.00197	5582.35	0.02	5556	5589
5	0.637	0.00948	5592.45	0.03	5589	5594
6	0.613	0.00622	5592.39	0.03	5589	5594
8	0.639	-0.01150	5592.44	0.01	5589	5594
9	0.620	0.00693	5592.44	0.03	5589	5594
5	0.911	0.05304	5598.45	0.02	5594	5601
6	0.886	0.05647	5598.37	0.02	5594	5601
8	0.920	0.05879	5598.43	0.06	5594	5601
9	0.897	0.05507	5598.42	0.02	5594	5601
5	1.101	0.00862	5604.94	0.02	5601	5607
6	1.087	0.00853	5604.85	0.01	5601	5607
8	1.109	0.00625	5604.86	0.01	5601	5607
9	1.090	0.00695	5604.91	0.01	5601	5607
5	1.084	-0.00690	5613.41	0.01	5607	5618
6	1.074	-0.00405	5613.61	0.02	5607	5618
8	1.091	-0.00438	5613.64	0.01	5607	5618
9	1.081	-0.00383	5613.35	0.02	5607	5618

Table 4. Quadratic fits to UTC(USNO,MC) – TID(FTS)

Medium	Offset (a), μs	Rate (b), $\mu s/d$	Drift/2 (c), $\mu s/d/d$	Average time ($\bar{t}$), MJD	Standard error (σ), μs
SV(5)	-8.485	-0.06867	-0.0001853	5574.96	0.019
SV(6)	-8.334	-0.06841	-0.0001663	5572.08	0.010
SV(8)	-8.478	-0.06904	-0.0001788	5574.46	0.019
SV(9)	-8.510	-0.06924	-0.0001817	5575.86	0.022
All SV	-8.387	-0.06849	-0.0001764	5573.39	0.017
GPS TIME, SV(5)	-8.483	-0.06893	-0.0001872	5574.96	0.023
GPS TIME, SV(6)	-8.326	-0.06851	-0.0001752	5572.08	0.016
GPS TIME, SV(8)	-8.472	-0.06925	-0.0001896	5574.46	0.022
GPS TIME, SV(9)	-8.523	-0.06969	-0.0001830	5575.86	0.017
GPS TIME, all SV	-8.385	-0.06872	-0.0001869	5573.39	0.015
Common view	-8.559	-0.07054	-0.0001614	5573.50	0.023
UTC(USNO, MC) – UTC(AUS) via GPS TIME, all SV	-12.19	-0.01680	0.0	5576.92	0.088

Table 5. Contributors to UTC(AUS), July–October 1983

Organization	Location	Time standards
Tidbinbilla DSCC	Canberra	1 hydrogen maser 2 HP caesium standards
Division of National Mapping	Canberra	2 HP caesium standards
Orroral Valley STDN	Canberra	1 HP caesium standard
CSIRO National Measurements Lab	Sydney	2 hydrogen masers 3 HP caesium standards
Royal Australian Navy	Sydney	1 HP caesium standard
TELECOM Australian Research Lab	Melbourne	5 HP caesium standards

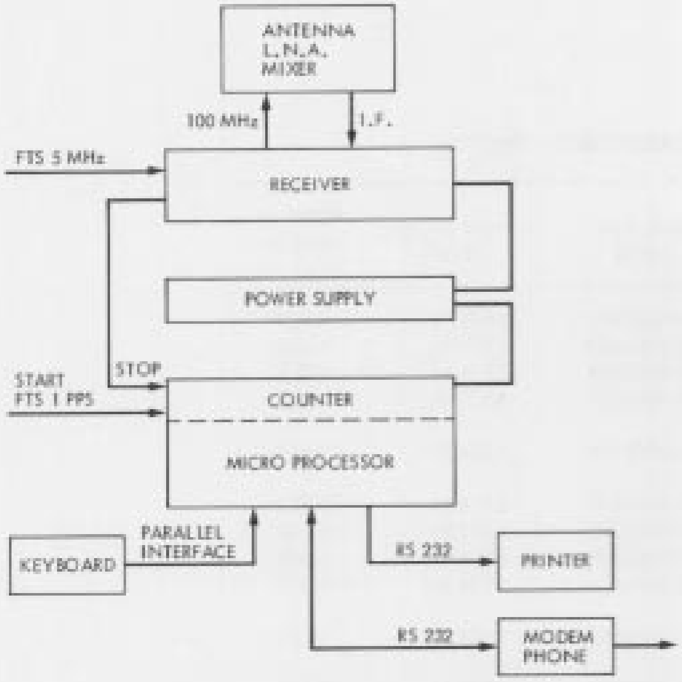

Fig. 1. GPS equipment configuration at Canberra Deep Space Communications Complex, Tidbinbilla

Fig. 2. GPS receiver installation at Tidbinbilla

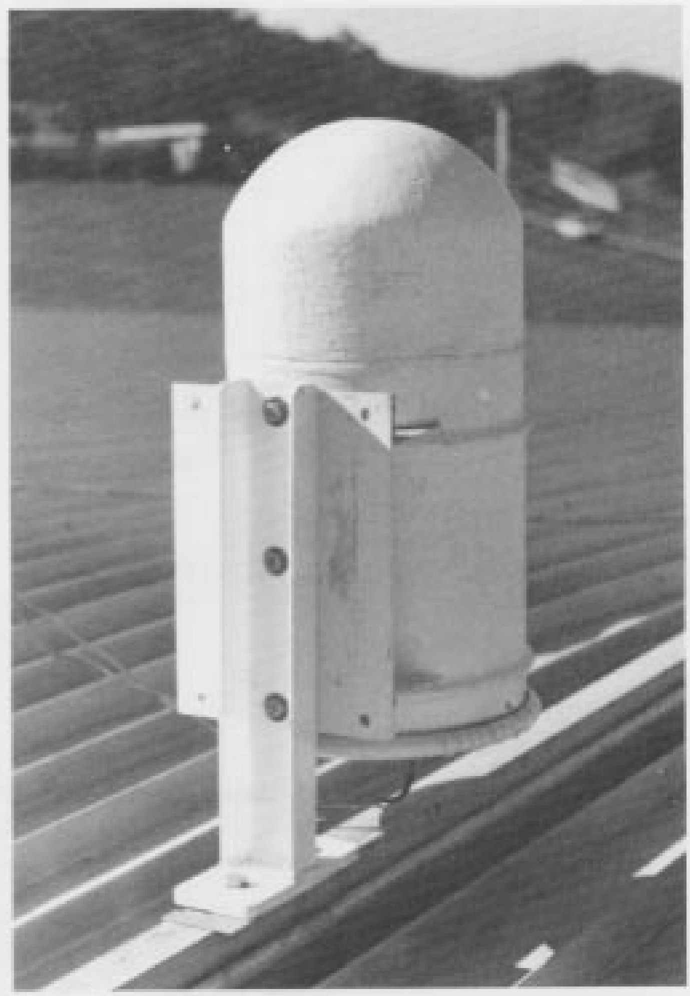

Fig. 3. GPS antenna housing on roof of CDSCC

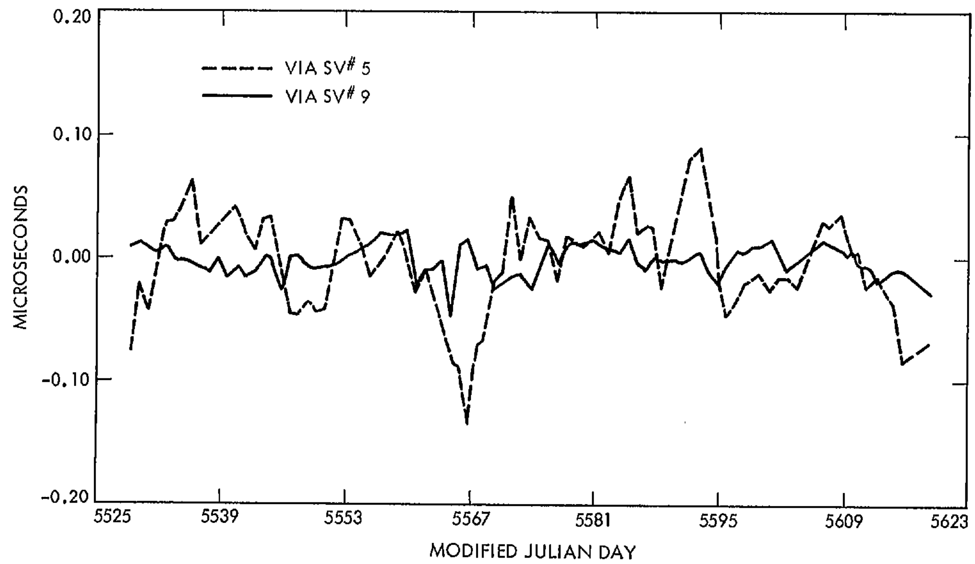

Fig. 4. Residuals from quadratic fits through raw data TID(FTS) – SV TIME, space vehicles 5 and 9 (see Table 1)

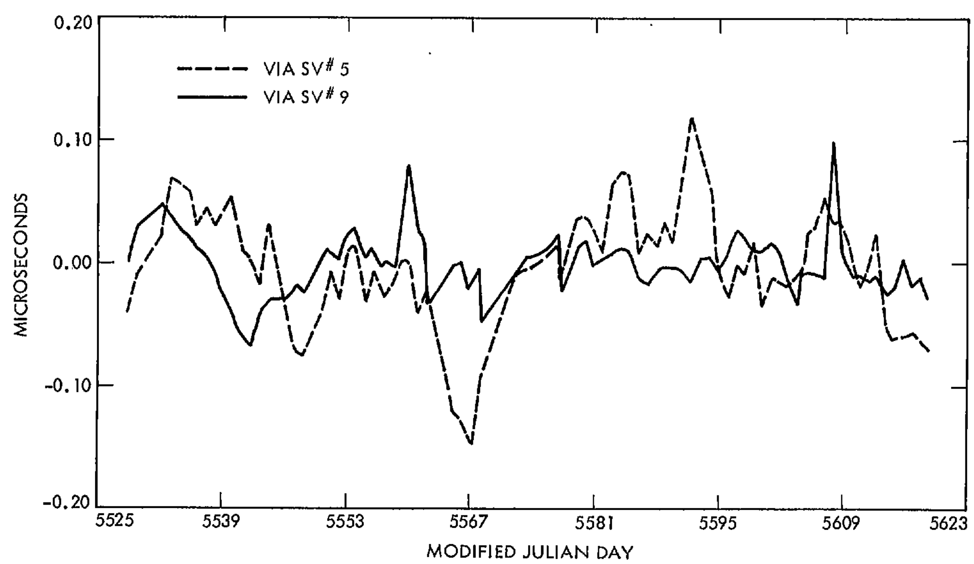

Fig. 5. Residuals from quadratic fits through raw data UTC(UNSNO,MC) – SV TIME, space vehicles 5 and 9 (see Table 1)

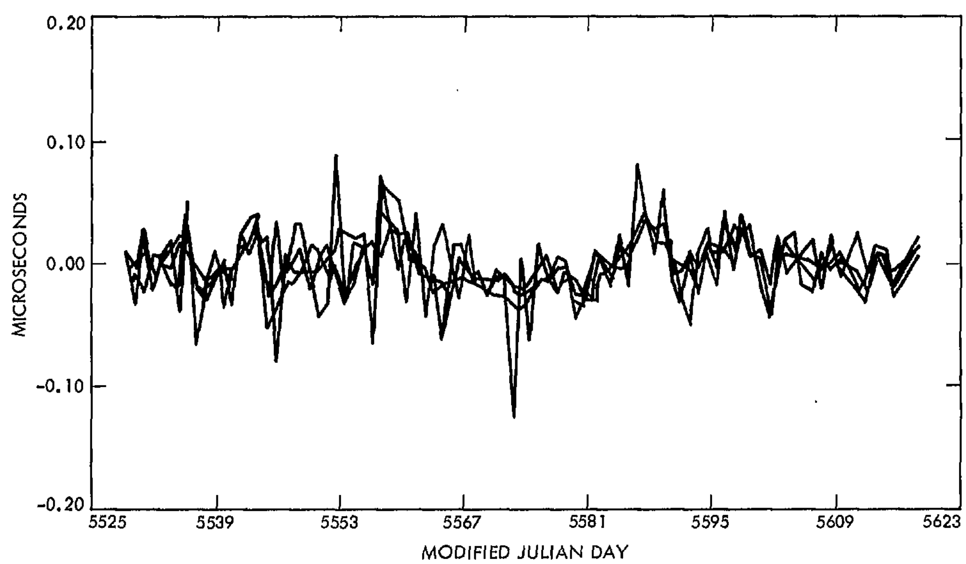

Fig. 6. Residuals from straight line fits through raw data TID(FTS) – GPS TIME, space vehicles 5, 6, 8, 9 segmented at MJDs 5532, 5542, 5556, 5589, 5594, 5601, 5607 and 5618 (see Table 2)

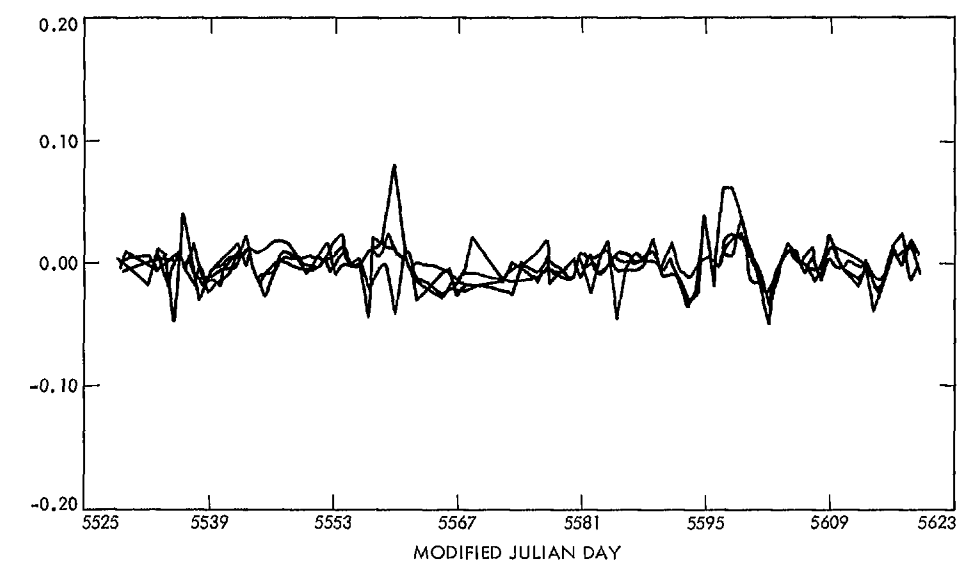

Fig. 7. Residuals from straight line fits through raw data UTC(USNO,MC) – GPS TIME via space vehicles 5, 6, 8, 9, as in Fig. 6 (see Table 3)

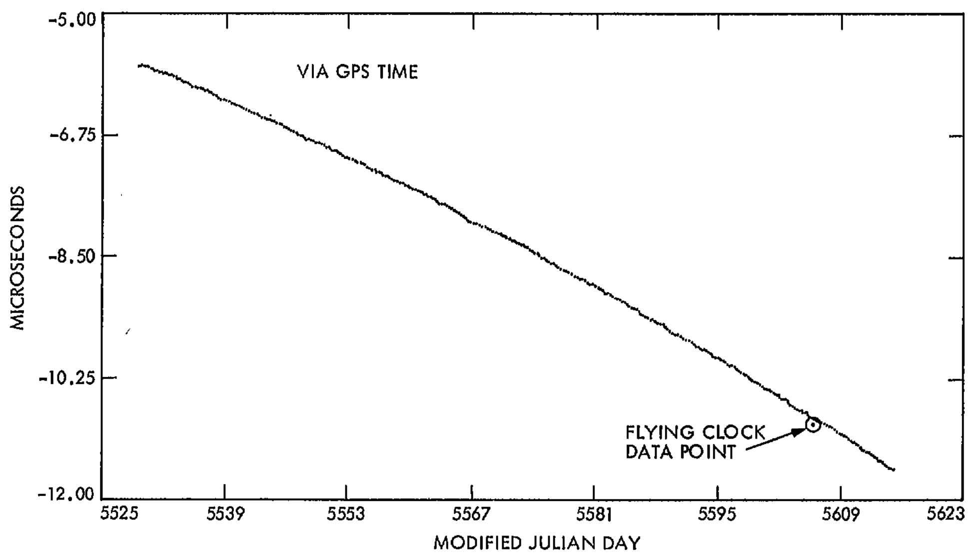

Fig. 8. Interpolated UTC(USNO,MC) – TID(FTS) using GPS TIME from space vehicles 5, 6, 8, 9 together

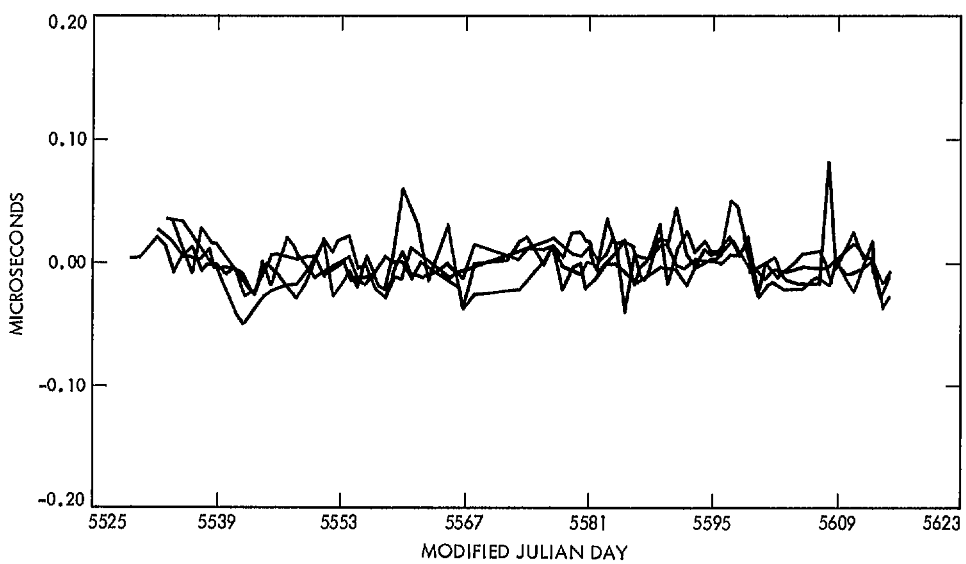

Fig. 9. Residuals from quadratic fits through interpolated data UTC(USNO,MC) – TID(FTS), using SV TIME from space vehicles 5, 6, 8, 9 (see Table 4)

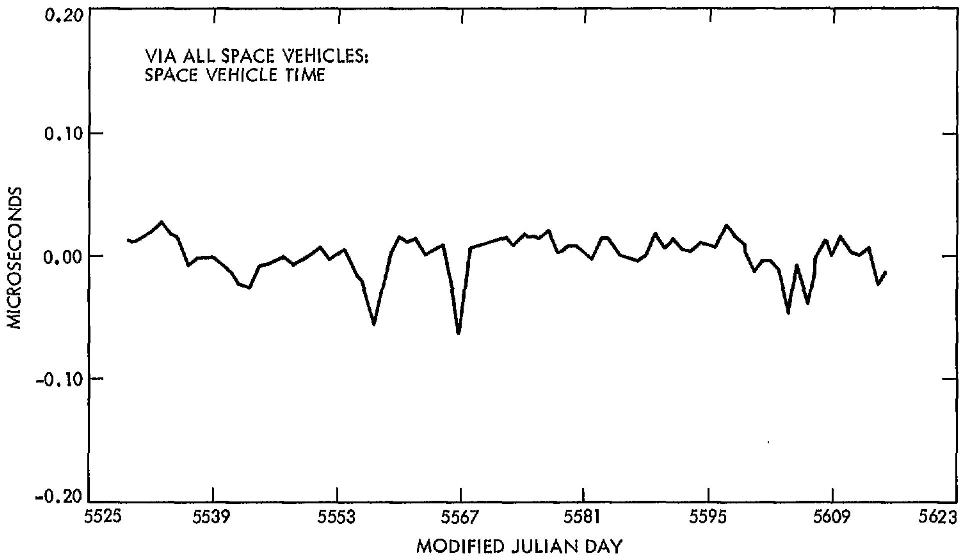

Fig. 10. Residuals from quadratic fit through interpolated data UTC(USNO,MC) – TID(FTS) reduced to 0*h* UTC and averaged over SV TIME from space vehicles 5, 6, 8 and 9 (see Table 4)

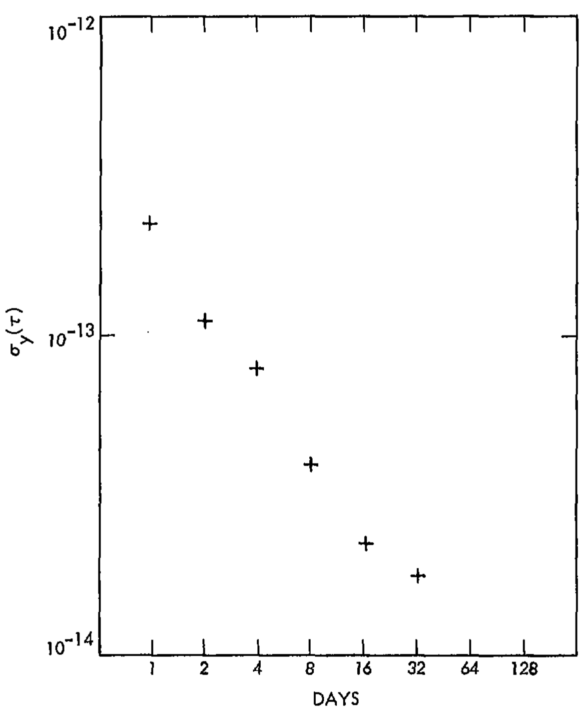

Fig. 11. Allan variances of residuals in Fig. 10

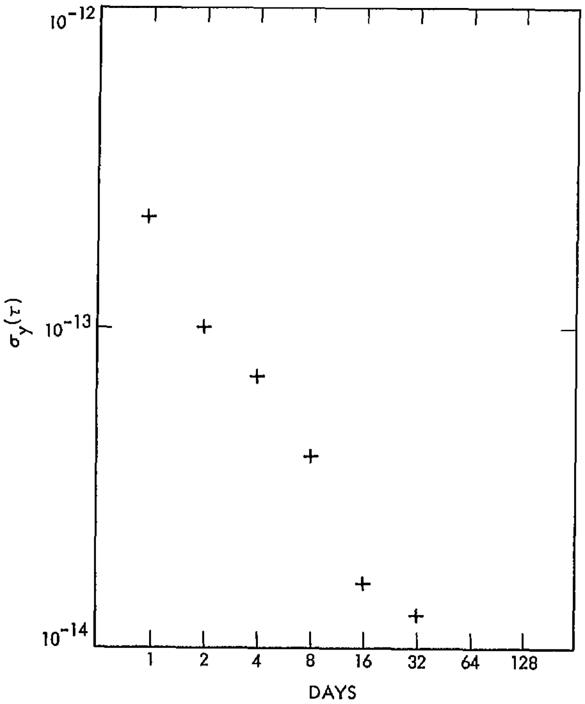

Fig. 12. Allan variances of residuals in Fig. 14

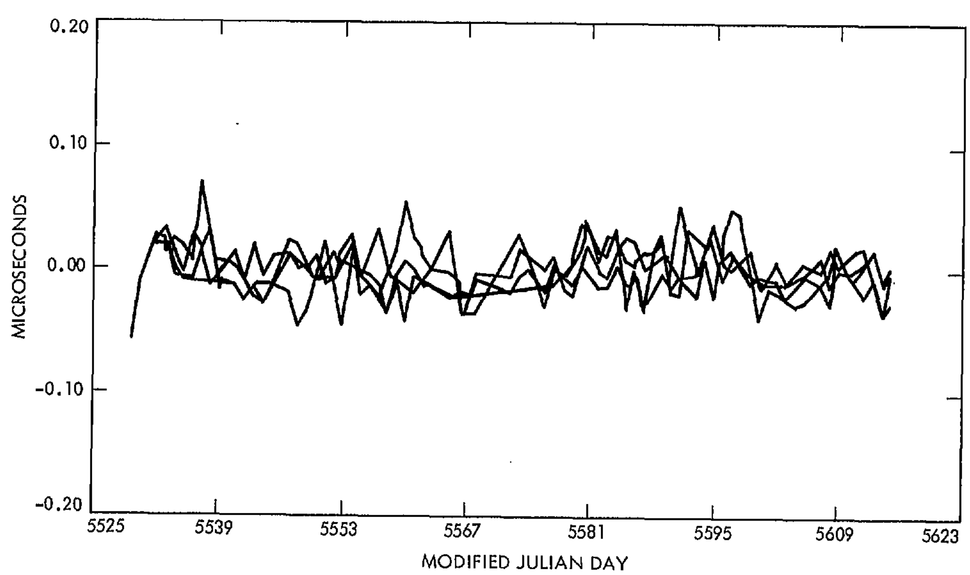

Fig. 13. Residuals from quadratic fits through interpolated data UTC(USNO,MC) – TID(FTS) using GPS TIME from space vehicles 5, 6, 8 and 9 (see Table 4)

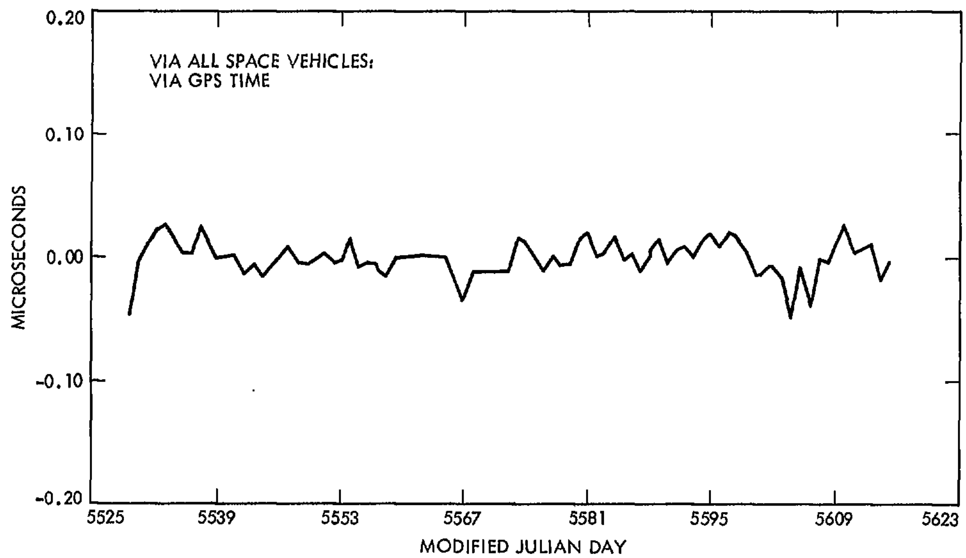

Fig. 14. Residuals from quadratic fit through interpolated data UTC(USNO,MC) – TID(FTS) reduced to O*h* UTC and averaged over GPS TIME from space vehicles 5, 6, 8 and 9 (see Table 4)

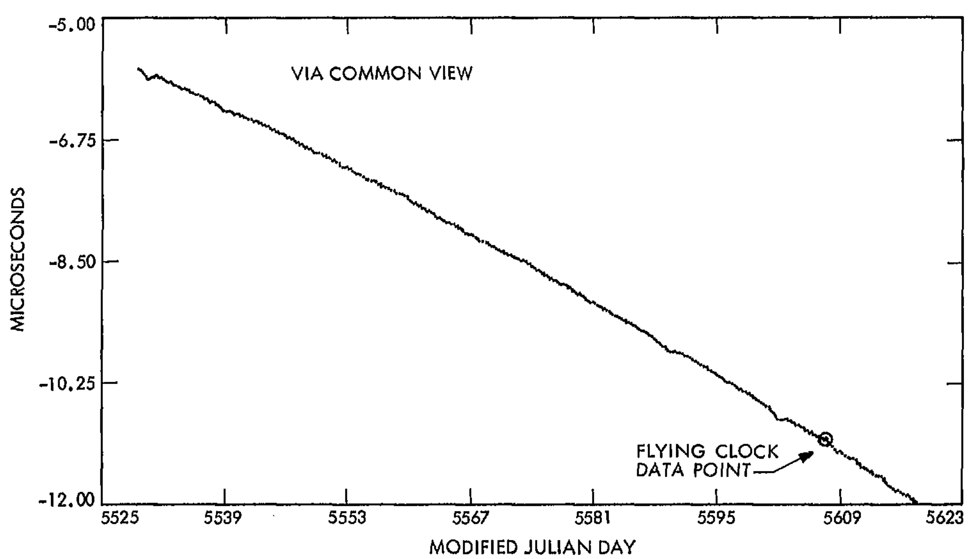

Fig. 15. Common view results UTC(USNO,MC) – TID(FTS) showing flying clock result on 1 October 1983

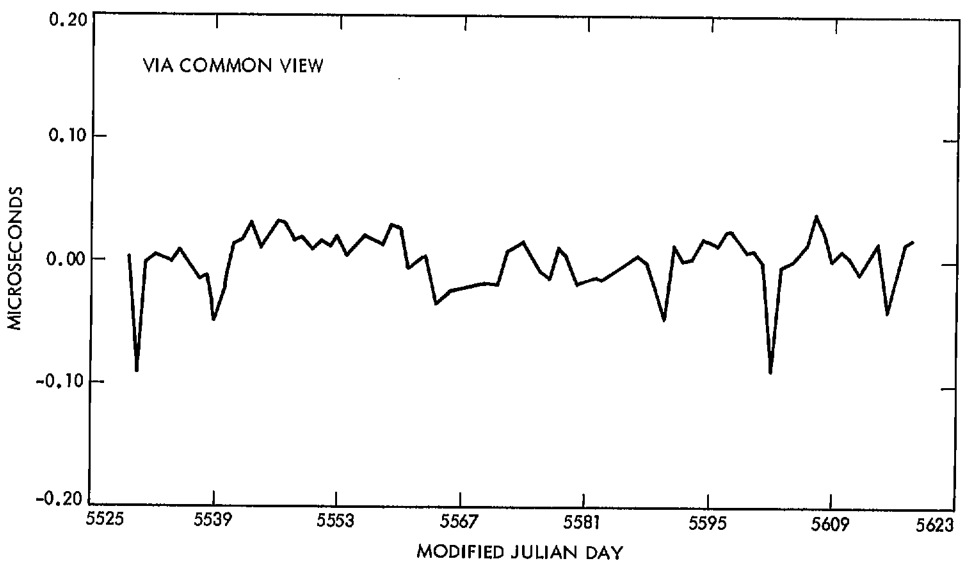

Fig. 16. Residuals from quadratic fit through common view results UTC(USNO,MC) – TID(FTS), averaged over GPS TIME from space vehicles 5, 6, 8 and 9 (see Table 4)

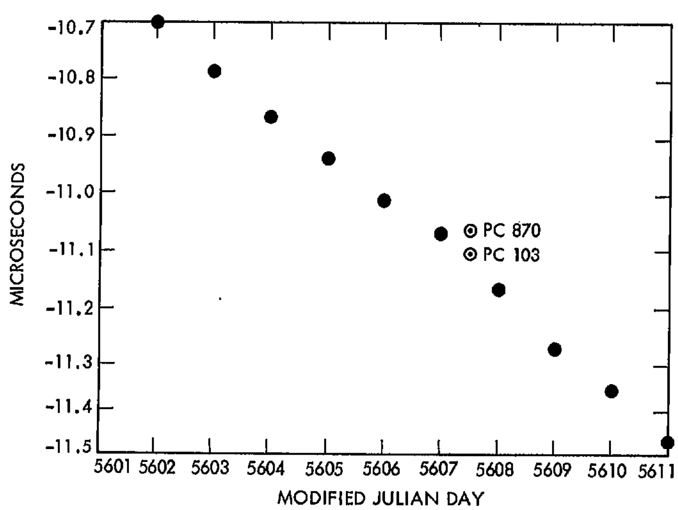

Fig. 17. Common view UTC(USNO,MC) – TID(FTS) in vicinity of travelling clock data points on 1 October 1983; "consolidated" from GPS TIME results on *0h* UTC

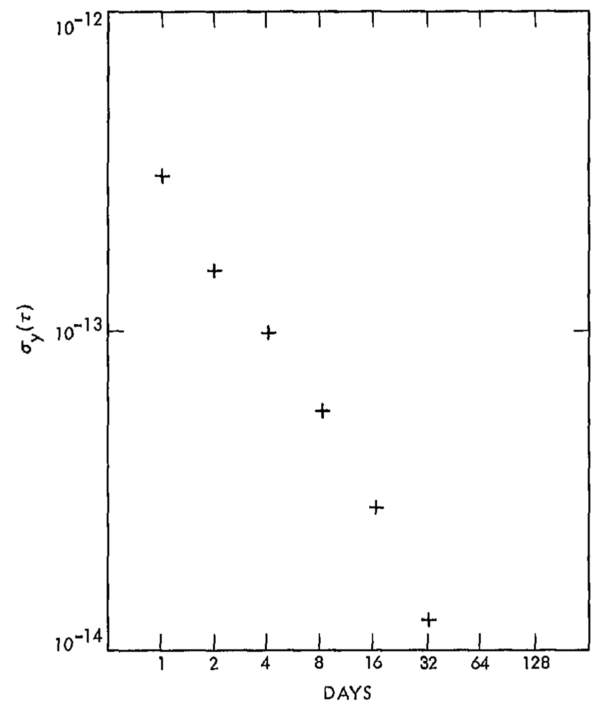

Fig. 18. Allan variances from quadratic fit through data of Fig. 17 (see Table 4)

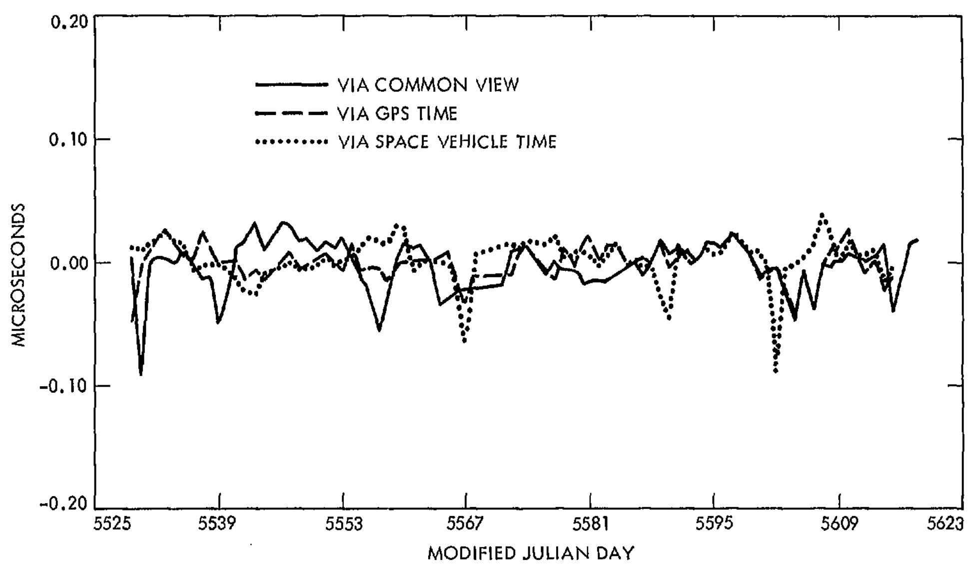

Fig. 19. Composite of residuals from quadratic fits through UTC(USNO,MC) – TID(FTS) via common view (Fig. 16), long-arc GPS TIME (Fig. 14) and long-arc SV TIME (Fig. 10)

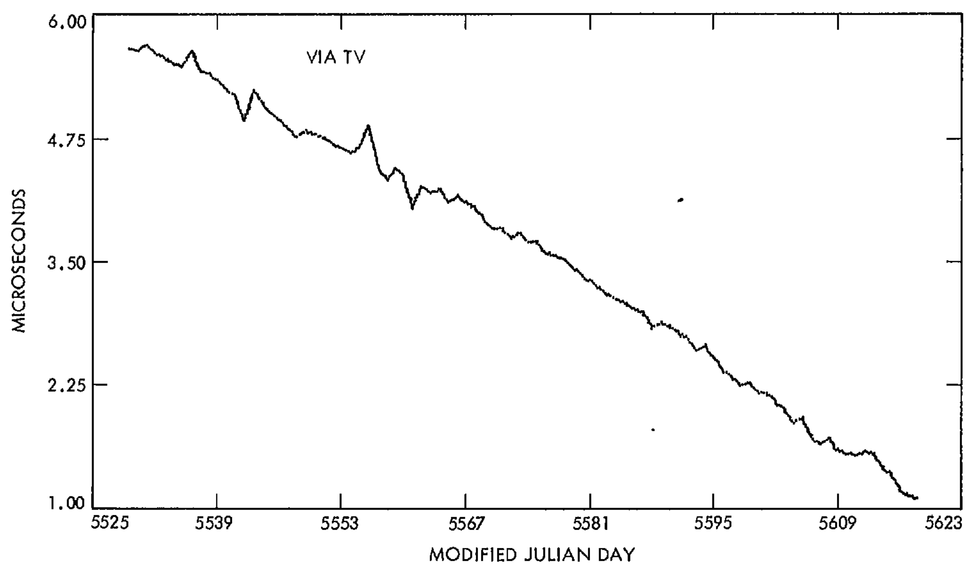

Fig. 20. UTC(AUS) – TID(FTS) via TV as published in NATMAP Bulletin E

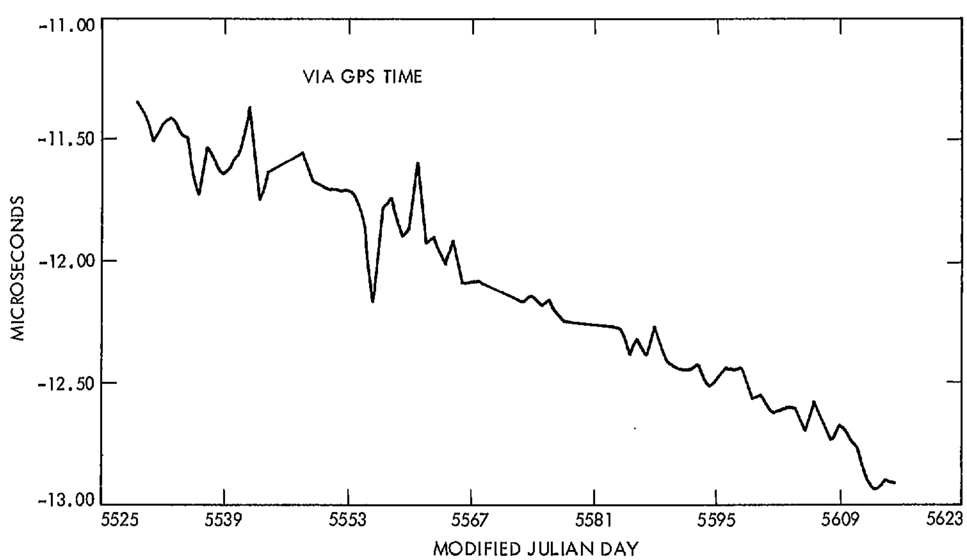

Fig. 21. UTC(USNO,MC) – UTS(AUS) derived from long-arc GPS TIME results to Tidbinbilla (Fig. 8) and Bulletin E (Fig. 20)

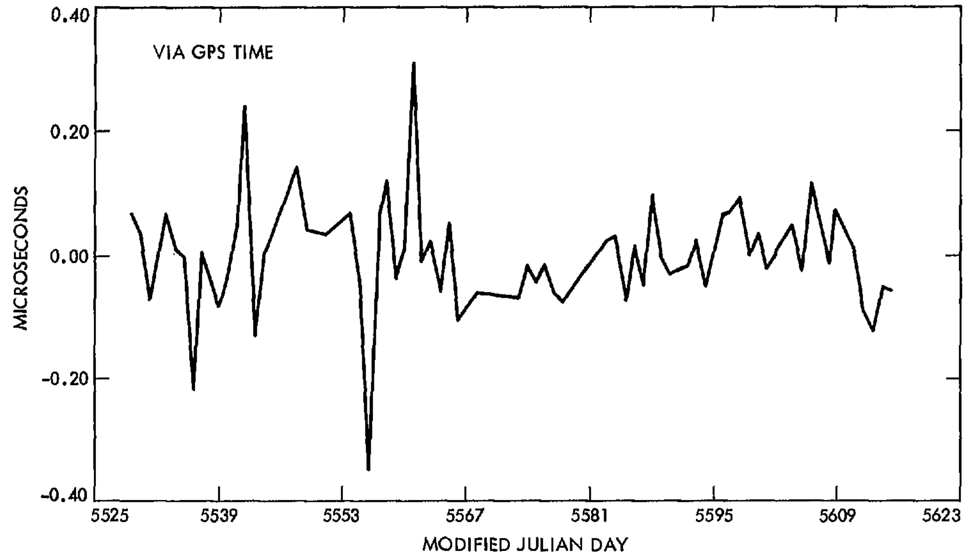

Fig. 22. Residuals from straight line fit through UTC(USNO,MC) – UTC(AUS) shown in Fig. 21 (see Table 4)

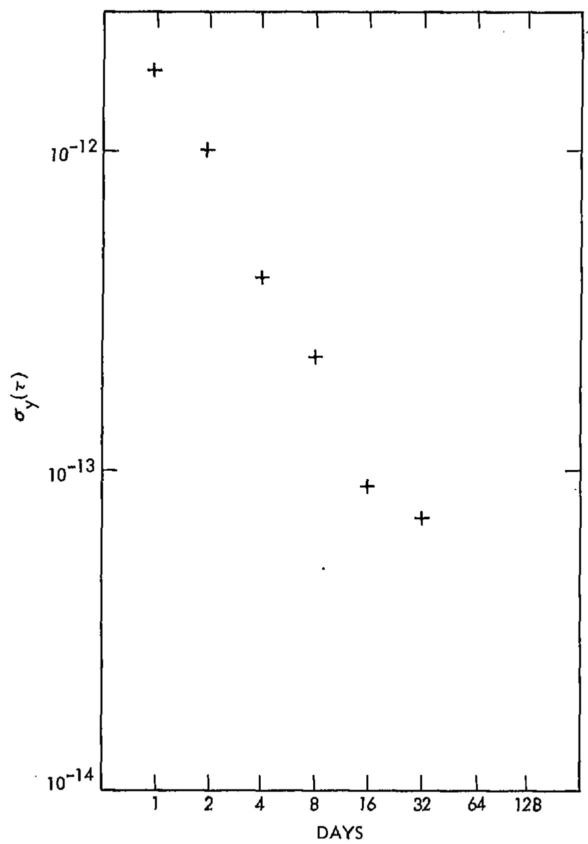

Fig. 23. Allan variances of the residuals UTC(USNO,MC) – UTC(AUS) shown in Fig. 22