PRECISE CLOCK SOLUTIONS USING CARRIER PHASE FROM GPS RECEIVERS IN THE INTERNATIONAL GPS SERVICE

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Abstract

As one of its activities as an Analysis Center in the International GPS Service (IGS), the Jet Propulsion Laboratory (JPL) uses data from a globally distributed network of geodetic-quality GPS receivers to estimate precise clock solutions, relative to a chosen reference, for both the GPS satellites and GPS receiver internal clocks, every day. The GPS constellation and ground network provide geometrical strength resulting in formal errors of about 100 psec for these estimates.

Some of the receivers in the global IGS network contain high quality frequency references such as hydrogen masers. The clock solutions for such receivers are smooth at the 20-psec level on time scales of a few minutes. There are occasional (daily to weekly) shifts at the microsec level, symptomatic of receiver resets, and 200-psec-level discontinuities at midnight due to 1-day processing boundaries.

Relative clock solutions among 22 IGS sites proposed as "fiducials" in the IGS/BIPM pilot project have been examined over a recent 4-week period. This allows a quantitative measure of receiver reset frequency as a function of site. For days and sites without resets, the Allan deviation of the relative clock solutions is also computed for subdaily values of τ.

TWO-STATION EXAMPLE

Figure 1 shows the network of geodetic-quality receivers in the International GPS Service. A number of these use hydrogen maser frequency references, some of which have been proposed as timing fiducials in the IGS/BIPM pilot project (`http://maia.usno.navy.mil/gpst.html`) to use the phase of the GPS carrier in time transfer (e.g.[1]). These sites are indicated by large circles in Figure 1.

The GPS phase and pseudorange observables are modeled as

$$L_r^x = \rho_r^x + b_r^x + z_r^x + \omega_r^x + C_r - c^x + \nu_r^x \quad (1)$$

and

$$P_r^x = \rho_r^x + z_r^x + C_r - c^x + \eta_r^x, \quad (2)$$

where L_r^x (P_r^x) is the measured phase (pseudorange) between transmitter x and receiver r, ρ_r^x is the range, b_r^x is phase bias, z_r^x is the troposphere delay, ω_r^x is the phase windup, C_r is receiver clock, c^x is transmitter clock, and ν_r^x (η_r^x) is the phase (pseudorange) noise. One receiver clock is chosen as a reference; all clock solutions are relative to the reference. No *a priori* correlations are assumed among clock solutions.

At JPL's IGS Analysis Center, each day a subset of 37 stations in Figure 1 is selected with good geographic distribution. Data from this subset are used to estimate precise transmitter parameters[2]. Receiver parameters from sites not in the subset can be determined with precise point positioning[3]. The formal error of each estimated clock is about 100 psec (3 cm).

Figure 2 shows the Madrid, Spain (`mad2`) clock estimate minus the Tidbinbilla, Australia (`tid2`) clock estimate during April, 1998. The difference is piecewise linear with occasional μsec-level shifts. The shifts represent a change at one of the sites, usually a receiver-induced reset.

For this clock "baseline" the period April 17-30, 1998 is free of resets. The `mad2` – `tid2` difference has been de-trended for this period (the slope – about 7 nsec/day $\approx 8 \times 10^{-14}$ – is the result of a frequency offset between the two sites) and shown in Figure 3. Except for the 0.2-nsec-level shifts – due to 1-day processing boundaries – the solution is smooth at the 20-psec level.

IGS/BIPM CLOCK SITES, OCTOBER 1998

Information on stations in the IGS can be found at `http://igscb.jpl.nasa.gov`. The sites with 4-character IDs

```
algo brus drao fair fort gode gol2 hob2 irkt kokb mad2 mate nlib nyal nrc1 onsa pie1
tid2 usno wes2 wtzr yell
```

have been proposed as timing fiducials in the IGS/BIPM pilot project. For each day during the 4-week period beginning October 4, 1998, we have computed the relative clock estimates among all clock baselines, and then computed the Allan deviation $\sigma(\tau)$

$$\sigma(\tau) = \sqrt{\frac{\sum_{i=1}^{N-2m} (x_{i+2m} - 2x_{i+m} + x_i)^2}{2(N-2m)\tau^2}}, \quad (3)$$

where $m = \tau/\tau_o = 1, 2, 4, 8, ...64$ and $\tau_o = 300$ sec is the spacing of data used in parameter estimation. In (3), x_i indicates the i^{th} difference in clock estimates between the two sites that form the baseline.

In the event that a given receiver has a sufficiently large discontinuity in its clock during the day, the Allan deviation of that receiver with respect to any other will be anomalously large. This suggests that, to determine whether a given receiver had a shift during the day, one should look at its Allan deviation with respect to all other receivers, and choose the smallest. If this is sufficiently small, it did not have a shift during that day.

Figure 4 gives an example for October 27, 1998. For each site indicated on the abcissa, the values of $\sigma(\tau)$ for that site with respect to other sites are plotted as ordinates. It is clear that four sites – `fort`, `gode`, `hob2` and `nlib` – have variations on that day that are large with respect to the other sites. In Figure 4 we have taken $\tau = 600$ s, although the character of such a plot is the same for other values of τ.

For each receiver, day, and τ, we have computed the smallest $\sigma(\tau)$. The median values over the 4-week period are given in Table 1. (Median is used because it is insensitive to outliers.) On a given day, if a receiver can be paired with no other to achieve $\sigma(\tau) < 10^{-12.9}$ for $\tau = 600$ s, then that receiver is assumed to have a shift during that day. The number of such days are given as the last column in the table. Because it was disconnected from its H maser during most of October (IGS Mail 2034, October 2, 1998, `ftp://igscb.jpl.nasa.gov/igscb/mail/igsmail/igsmess.2034`) the results for `hob2` (Hobart, Tasmania) are indicative of the receiver's internal oscillator.

As an example, the results using this methodology for the clock at Algonquin Park, Canada (`algo`) are plotted in Figure 5.

CONCLUSIONS

Of 22 sites proposed for use in the IGS/BIPM pilot project, four exhibited no resets during the 4-week period beginning October 4, 1998. For 17 others (excluding 1 which was using its internal oscillator), there were typically 1 to 9 days where the receiver exhibited a reset. Allan deviations are typically $\log_{10}\sigma(\tau) \approx -13.2 \pm 0.1$ at $\tau = 300$ s to $\log_{10}\sigma(\tau) \approx -14.2 \pm 0.3$ at $\tau = 19200$ s.

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REFERENCES

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[2] J. F. Zumberge, M. M. Watkins and F. H. Webb 1998, *"Characteristics and Applications of Precise GPS Clock Solutions Every 30 Seconds,"* **Navigation** , **44**, 4, 449-456.

[3] J. F. Zumberge, M. B. Heflin, D. C. Jefferson, M. M. Watkins and F. H. Webb 1997, *"Precise point positioning for the efficient and robust analysis of GPS data from large networks,"* **J. Geophys. Res**, **102**, B3, 5005-5017.

site τ	300 s	600 s	1200 s	2400 s	4800 s	9600 s	19200 s	*shift days*
algo	-13.32	-13.56	-13.78	-13.95	-14.14	-14.28	-14.40	0
brus	-13.21	-13.27	-13.31	-13.43	-13.54	-13.53	-13.75	2
drao	-13.32	-13.54	-13.73	-13.91	-14.06	-14.18	-14.32	1
fair	-13.25	-13.50	-13.73	-13.89	-14.10	-14.23	-14.51	6
fort	-13.02	-13.19	-13.44	-13.64	-13.71	-13.68	-13.60	9
gode	-13.32	-13.49	-13.72	-13.90	-13.98	-14.05	-13.99	6
gol2	-13.25	-13.49	-13.73	-13.94	-14.13	-14.26	-14.41	7
hob2	-9.20	-9.42	-9.70	-9.99	-10.30	-10.60	-10.89	23
irkt	-12.69	-12.96	-13.21	-13.47	-13.66	-13.85	-13.98	10
kokb	-13.20	-13.36	-13.54	-13.75	-13 93	-14.10	-14.25	4
mad2	-13.26	-13.44	-13.61	-13.82	-13.99	-14.15	-14.28	6
mate	-13.25	-13.35	-13.50	-13.68	-13.84	-13.87	-13.85	9
nlib	-13.27	-13.49	-13.66	-13.77	-13.99	-14.11	-14.20	4
nyal	-13.14	-13.36	-13.58	-13.77	-13.93	-14.04	-13.64	8
nrc1	-13.28	-13.48	-13.67	-13.80	-14.00	-14.14	-14.31	3
onsa	-13.28	-13.47	-13.65	-13.83	-13.98	-14.11	-14.24	3
pie1	-13.31	-13.53	-13.74	-13.93	-14.11	-14.32	-14.52	0
tid2	-13.13	-13.35	-13.57	-13.78	-13.92	-14.01	-14.11	0
usno	-13.25	-13.50	-13.75	-13.93	-14.13	-14.33	-14.54	0
wes2	-13.31	-13.51	-13.74	-13.90	-14.04	-14.07	-14.14	1
wtzr	-13.14	-13.32	-13.51	-13.70	-13.93	-14.10	-14.21	1
yell	-13.15	-13.39	-13.60	-13.75	-13.92	-13.98	-14.22	6

Table 1: Allan deviation $\log_{10} \sigma(\tau)$ as a function of site for subdaily values of τ. The ***shift days*** column counts how many days during the 4-week period beginning October 4, 1998 the receiver clock exhibited a step function. Note that the H maser at **hob2** was not connected to the receiver for nearly all of October, so that results for it characterize the receiver's internal oscillator.

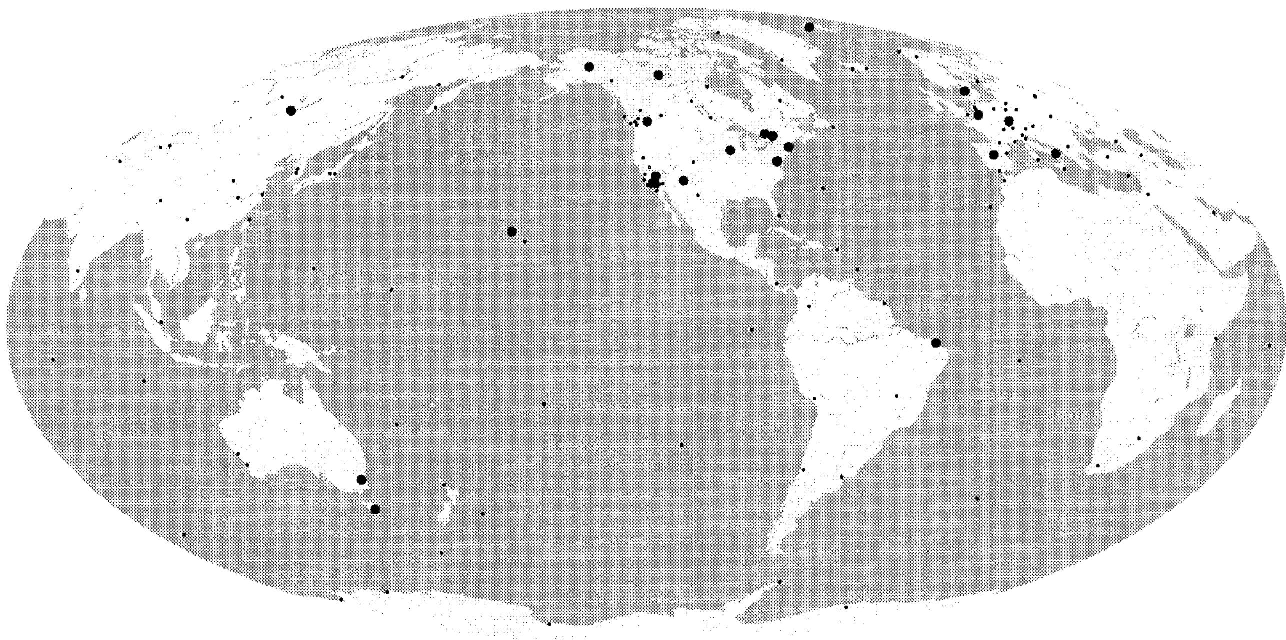

Figure 1: The IGS network as of Oct 15, 1998. The large circles indicate sites proposed as timing fiducials in the IGS/BIPM pilot project.

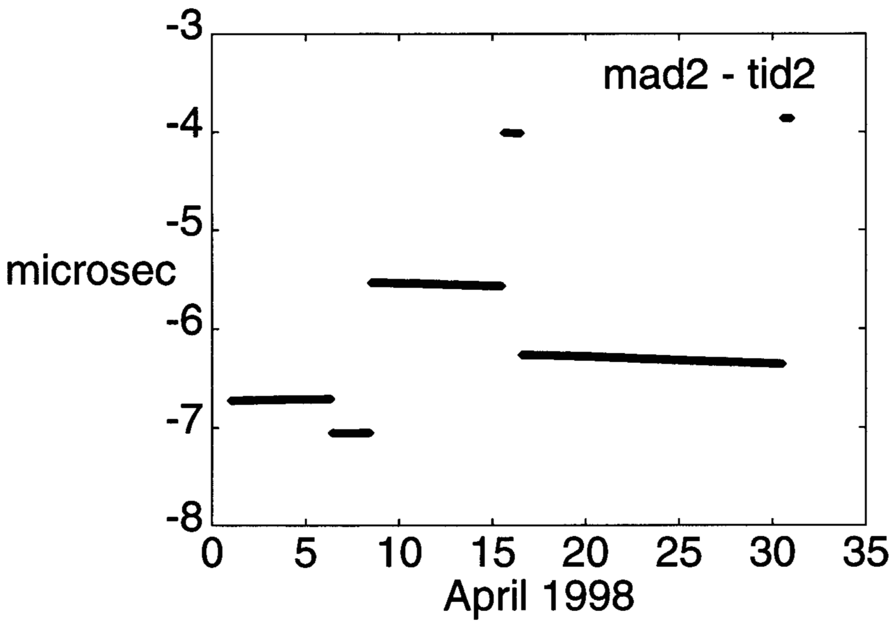

Figure 2: The Madrid, Spain clock solution minus the Tidbinbilla, Australia clock solution, during April, 1998. The difference is piecewise linear with occasional μsec-level shifts. The shifts are presumably symptoms of changes at one or both of the sites.

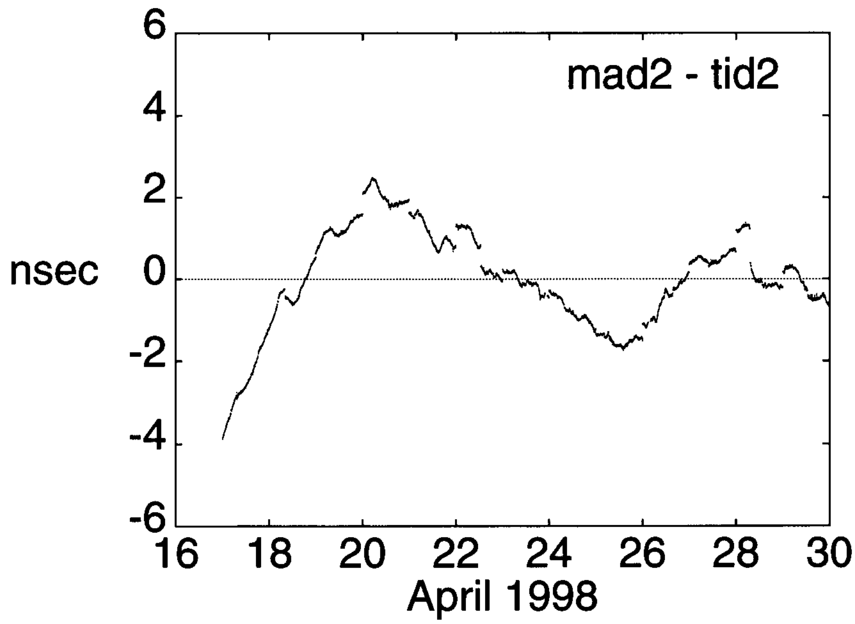

Figure 3: The Madrid, Spain clock solution minus the Tidbinbilla, Australia clock solution, for April 17-30, 1998. The difference has been de-trended (the slope is about 7 nsec/day $\approx 8 \times 10^{-14}$). Except for the 0.2-nsec-level shifts – due to 1-day processing boundaries – the solution is smooth at the 20-psec level.

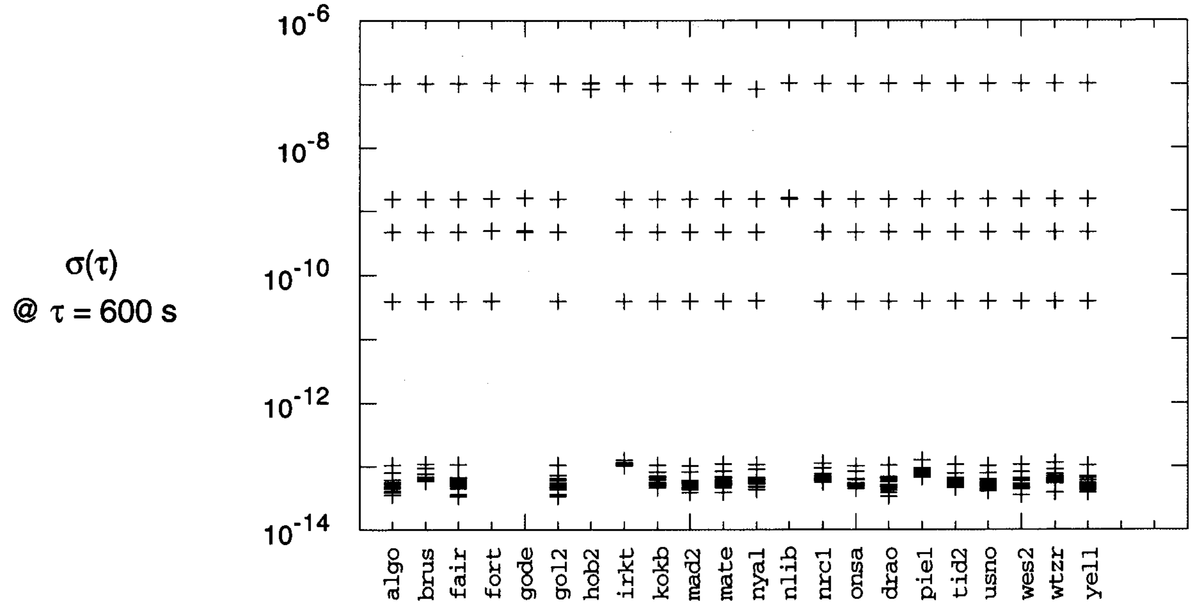

Figure 4: The Allan deviation at $\tau = 600$ s on October 27, 1998, for all baselines among the 22 proposed timing fiducials. The figure indicates that none of the four sites **fort**, **gode**, **hob2**, **nlib** could be paired with any site to achieve $\log_{10}\sigma(\tau) < -12.9$.

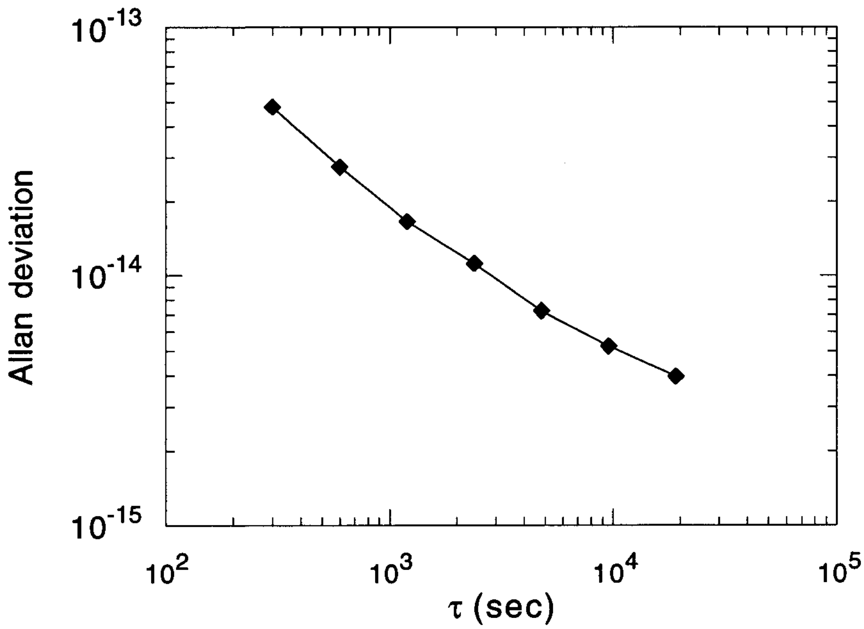

Figure 5: The Allan deviation for Algonquin Park, Canada; see text for methodology. The logarithmic slope is -0.60.