A TEST OF PRECISION GPS CLOCK SYNCHRONIZATION

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ABSTRACT

This paper will describe tests Or precision GPS time transfer using geodetic-quality TurboRogue receivers. The GPS data are processed with the GIPSY-OASIS II software, which simultaneously estimates the GPS satellite orbits and clocks, receiver locations and clock offsets, as well as other parameters such as earth orientation. This GPS solution technique, which emphasizes high accuracy GPS orbit determination and observable modeling, has been shown to enable sub-1 ns time transfer at global distance scales, as reported in previous 1"1"1'1 conferences in 1991 and 1993.

GPS-based monitoring of clock performance has been carried out for several years through JPL's high precision GPS global network processing. This paper will discuss measurements of variations in relative clock offsets down to a level of a few tens or picoseconds. GPS-based clock frequency measurements will also be presented.

BACKGROUND

Global GPS (Global Positioning System) analyses at JPL have been done routinely on a daily basis since the start of the IGS (International GPS Service for Geodynamics) campaign in June Or 1992. Currently, GPS data from the 24 earth-orbiting GPS satellites and over 150 ground stations[1] are analyzed daily in a highly automated operational process using JPL'S GIPSY-OASIS II software [1]. Carrier phase measurements from all ground sites are processed, and pseudorange measurements are used on a site-by-site basis, as explained below. Data are decimated to 5-minute intervals, and multiple satellite and ground station parameters are estimated. These include the GPS orbits and station positions, satellite and station clocks (modeled as white noise), Earth orientation and polar motion, tropospheric delays, and solar radiation pressure. Ocean loading, solid earth tides, and satellite attitude effects are also modeled during processing.

Over [be. years, a significant contribution to realizing better clock solutions has been simply the growth of sad, more importantly, the improved distribution of ground receivers in the global GPS network. When AS (Anti-Spoofing) went into effect in January of 1994, clock solutions temporarily were degraded somewhat, due to effects on the pseudorange observables which were initially not properly modeled [2]. Currently, with AS routinely operational, pseudorange data from sites using the older Rogue GPS receiver models are excluded, while the pseudorange data from the modern TurboRogue and other types Or GPS receivers are generally included. The TurboRogue receivers produce ionospherically calibrated precise phase and pseudorange observables whether AS is on or off, without requiring knowledge of the Y-code. Adding pseudorange in this manner greatly improves clock results under AS conditions.

The global network used in daily analyses now consists or more than 150 GPS ground receivers or varying types. The frequency standards used at each station also vary. Most sites use the receiver's internal (quartz) oscillator as a clock; however, there are primarily three other external standards used: Rubidium, Cesium, and the Hydrogen Maser. The breakdown over the entire current network and some typical performance statistics are shown in Table 1.

Table 1: Global Network frequency standard makeup. Root mean square (RMS) values are typical results based 011 January 199624-111 GPS-based linear fits between the station clock and a reference maser

TYPE	NUMBER	RMS (as)
11-Maser	25	0.08-0.30
Cesium (Cs)	16	1-2
Rubidium (Rb)	11	1, ?(), 1()()
Quartz (steered)	*	80 - 100
Quartz (unsteered)	*	>1000"

*total number of quartz (steered and unsteered) = 102

It is interesting to note that the observed noise performance 01 some or the internal quartz standards is statistically similar to SA (Selective Availability). This occurs for receivers whose internal oscillators are steered to GPS time, which is affected by SA at about the 70-ns level. This paper focuses (m results from II-maser stations in order to illustrate the accuracy obtained with precision GPS time transfer.

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[1] Global analysts only use the 37 best-distributed sites in the network on any given day; the remainder are analyzed separately via precise point-positioning based on the precise GPS orbit and clock solutions from the initial processing.

RESULTS

Figure 1 represents an example Of a typical one-day clock solution between two masers, one of which is used as the reference clock. The stations are located at Wetzell, Germany (WTZR) and Onsala, Sweden (ONSA); this baseline is about 900" Km. Both silts use TurboRogue receivers and therefore, pseudorange data from both were used in the analyses. The clock rate is '231.12' ns/day and the RMS of the residuals about a linear fit is 0.028 ns.

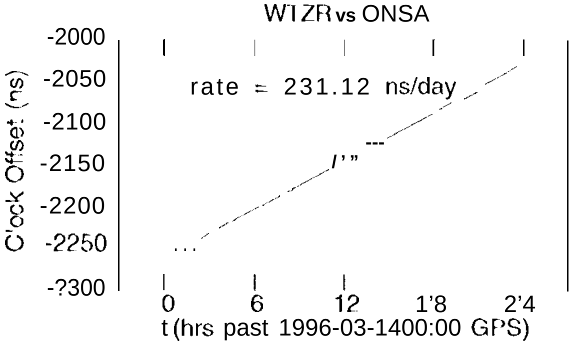

Figure 1: 24-hour H-Maser clock comparison with GPS. The rms about a linear fit is 0.028 ns.

The set of illustrations in Figure 2 shows a similar example of relative clock calibration with the precision GPS technique, but over a longer period of 72 hours, and over much longer baselines which range from about 2,800 to 12,100" Km. The three stations used in these plots again employ TurboRogue receivers and are located at Tidbinbilla, Australia (TID2); Algonquin Park, Ontario Canada (ALGO); and Pietown, New Mexico, USA (PIE1).

Three individual daily solutions were combined (for April 15-17, 1996; dotted lines indicate the day boundaries) and, as shown, the daily rates agree from one day to the next to within 1 ns/day (with one exception where a change of 1.6 ns/day over one day was measured), exemplifying the consistency of the GPS results and stability of the masers from day to day.

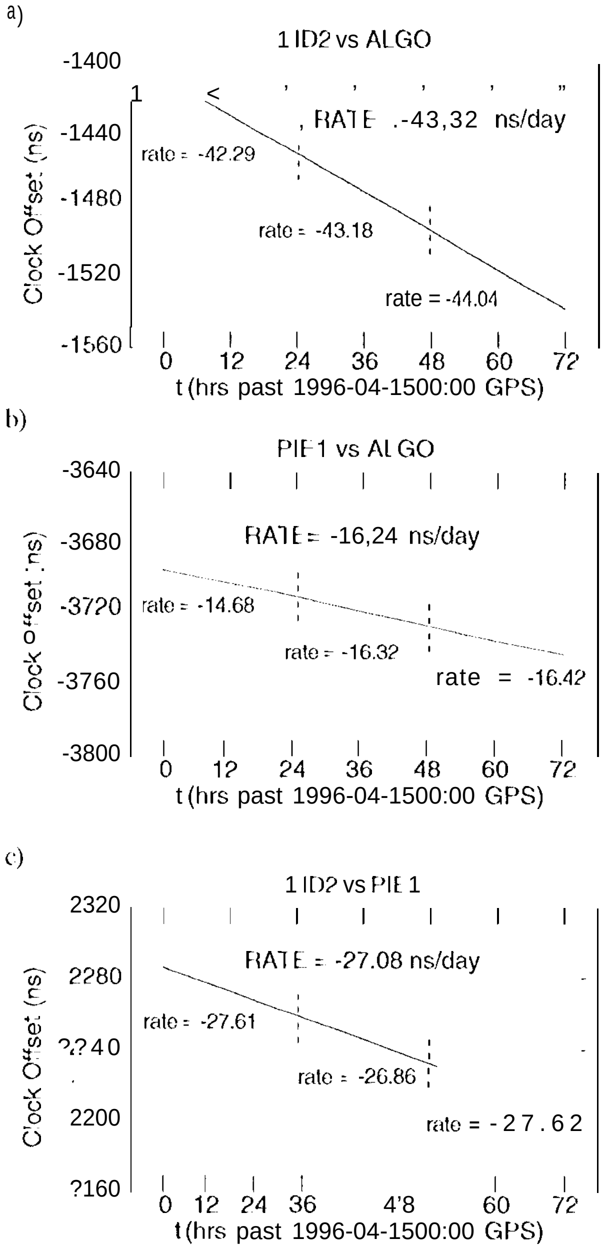

Figure 2a-c: 72-hour H-Maser clock comparisons with GPS. In Fig. 2a, the RMS about the three daily linear fits are 0.062, 0.159, and 0.088 ns; in Fig. 2b they are 0.111, 0.077, and 0.146 ns; in Fig. 2c they are 0.153, 0.180, and 0.128 ns.

Figure 3 represents the combined stability of the GPS technique and masers over the same 72-hour period. For each maser pair shown in Figure 2 above, a linear fit is done to the entire 3-day clock solution, and the respective residuals are plotted. The sub-ns residuals achieved over three days are indicative Of the precision of the GPS technique as well as the relative stability Of the masers.

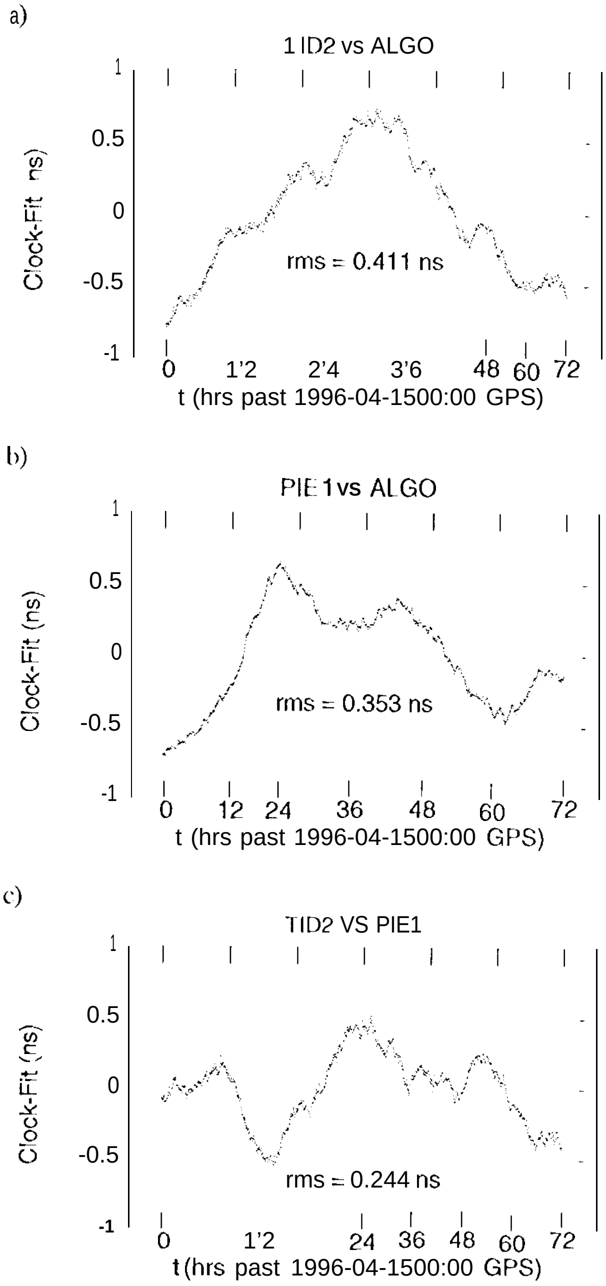

Figure 3a-c: 72-hour H-Maser linear fit residuals

The plots in Figure 4 show statistical behavior Of the GPS clock solutions over a variety of timescales. The Allan deviation (σ_y) of each baseline pair clock solution is shown, after removal Of a linear drift. It is apparent that the typical noise floor of the combined GPS time transfer plus a pair Of masers is between 4 x 10^{15} and 9 x 10^{-15} occurring between τ values of lo' and 10^5 seconds.

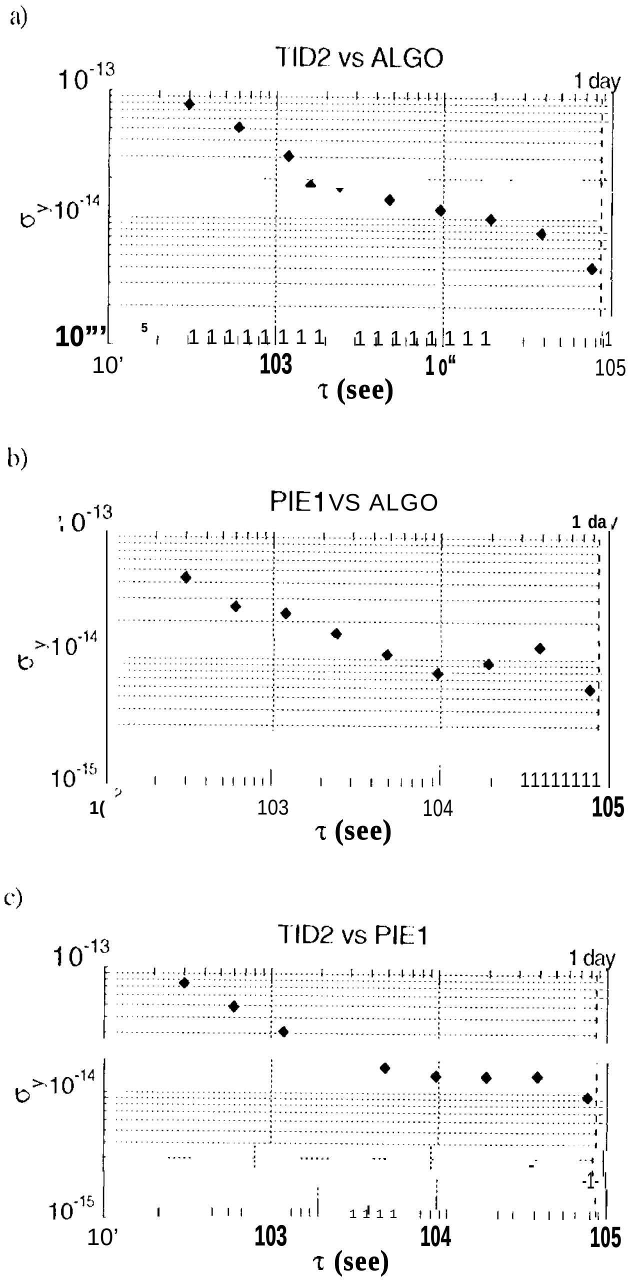

Figure 4a-c: 72-hour H-Maser Allan deviation

ERROR ANALYSIS

The accuracy of the chained clock solutions depends on a number of error components. These can include measurement noise, GPS signal multipath at the site, error in the satellite orbit, uncalibrated tropospheric delay, and instrumental delay. Figure 5 below is an estimate Of the GPS noise component due to instrumental delay variations. The Allan deviation for a 10-day (January 3-

12, 1996) clock solution between two receivers at the same exact location is shown. One of these receivers, CANB, is of the older Rogue type, and consequently, its pseudorange data were not included. As both of these receivers are connected to the same GPS antenna and use the same H-maser, all errors from satellite orbits, atmosphere, geodetic parameters, and the maser itself are effectively canceled, and effects from receiver noise and from multipath are largely eliminated as well. What remains is noise due to different changes in instrumental delays in the two receivers. The observed GPS measurement noise under these conditions is shown to be just [illegible] 5 x 10 ‘(’ for a τ of about 300,000 seconds.

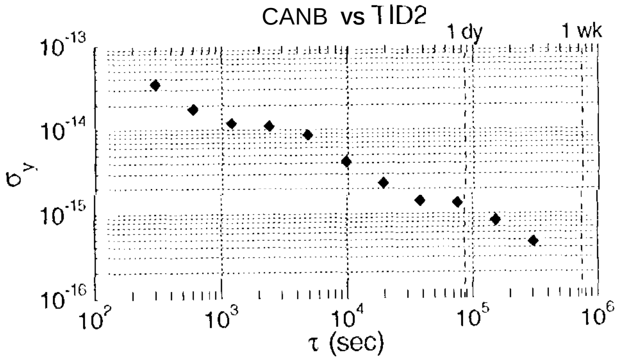

Figure 5: 10-day Allan deviation of GPS data for a "zero-baseline" case. Maser noise does not contribute to plot.

Global GPS estimation is a powerful tool for monitoring relative clock variations between different time standards. While the capability to determine absolute clock offsets is desirable, this requires exacting calibrations for all cable and hardware component delays in the receiver, and between the output of the clock or timing device and the output of the GPS receiver. At the present time we have evaluated performance for using GPS to perform a different, but still useful function: namely, the monitoring of clock or time standard stability and frequency changes through relative clock and frequency offset estimation. Such a function is extremely important at observatories and spacecraft tracking facilities, such as the NASA/JPL Deep Space Network, where high levels of performance of very high accuracy time standards (such as hydrogen masers) are essential. In addition, GPS can be used to make comparative measurements between different time standards. The accuracy of the GPS technique for measuring relative clock offsets and stabilities can be inferred from statistics of GPS-based clock solutions for time standards which are known (or believed) to be very stable. In addition, certain errors or instability levels can be calculated analytically. In the following section, we provide approximate error budgets for GPS estimation of clock variations over two different time regimes: 1,000-sec, and 100,000 sec, corresponding to slightly more than 15 minutes and slightly more than one day.

The highest accuracy method for GPS-based estimation of clock offsets requires that precision models for GPS observables be utilized and that high accuracy estimation techniques be employed. This type of analysis at JPL dates from the mid-1980s, and most recently daily JPL GPS solutions have achieved accuracy of better than 1 cm globally for ground coordinate estimates, and accuracy of better than 15 cm for GPS orbits [1]. These solutions are produced every day at JPL, and the analysis is highly automated. The transmitter and receiver clocks, along with other parameters such as tropospheric path delays, Earth orientation, and GPS phase biases, are also determined. Independent tests have repeatedly confirmed that the overall system accuracy is extremely good. An error breakdown for system performance can be analytically calculated. These calculations have been done and have been shown to be consistent with other measures of accuracy involving independent comparisons with non-GPS techniques for the orbit, atmospheric and geodetic parameters which are estimated along with the clock parameters. For instance, GPS satellite positions have been independently measured with laser ranging; troposphere delays have been independently measured with water vapor radiometers; and geodetic parameters have been independently measured with laser ranging and very long baseline interferometry.

A 15-cm GPS orbit error projects to a differential range error of slightly less than 5 cm (about 0.15 ns) for two sites separated by the diameter of the Earth. Because the station clock estimate is actually based on an average of data from 8 GPS satellites, and since other parameters are also being estimated simultaneously one would expect that the actual station clock error from these orbit errors would be less. Figure 6 shows error budgets for the 1,000-sec and 100,000-sec time interval cases. We adopt the 0.15 ns value as a conservative estimate of GPS-based ground clock error from orbit effects. Such orbit-related effects, however, are manifested only after some time comparable to the GPS orbital period has passed, since over very short times these orbit errors would be highly correlated, appearing as a bias and therefore not observable over short time intervals for relative clock estimates. Hence the plot shows nearly zero orbital effect for the short time interval case (1,000 sec) and 0.15 ns for the 100,000 time interval case.

Other errors included in the plot are: troposphere high-frequency "noise" (from atmospheric fluctuations) and systematic troposphere mismodeling, the latter affecting the accuracy of the troposphere parameters estimated in the GPS analysis; cable and receiver instabilities (from temperature variations, for instance), which are important primarily for longer time intervals (greater than 12 hrs); and multipath, which is known to add a few mm of error to the carrier phase observable used to track short-term clock variations, and to add several cm of error to the pseudorange-based estimates of the carrier phase biases - the latter error persisting for each satellite track of about 10,000 sec duration. Ionospheric delays are corrected by dual-frequency combinations Of L1 and L2 GPS observables. The root sum square (RSS) of the c.1101"s, which are assumed to be independent, is about 0.02 ns for the short (1,()()()-see) timescale, and about 0.?2 ns for the lm~gcr(100,(K)()-scc) timescale.

The quantities shown in Fig. 6 represent typical anticipated performances based on current knowledge about the performance of the GPS analysis technique used al J]'],. However individual cases may be better than what is shown in Fig. 6. Multipath and troposphere tend to be fairly silt-specific, and lower errors than those shown in Fig. 6 for the 100,000-sec interval are not uncommon. For instance, the scatter about a linear fit shown in Fig. 1 for the Wetzell-Onsala clock comparison is considerably better than the 0.'2 ns expected from Fig. 6. The reasons for this are several: due to the relatively short separation of these two sites (about 900 Km), there is significant orbit error cancellation (about a factor of ten as compared to the 10,000 km distance assumed for the 0.2 ns case in Fig. 6); also, relatively close-by sites may have similar temperature conditions and thus temperature-induced variations in hardware may be common and partially cancel. The clock estimate scatters over the longer baselines shown in Fig. 3 and over the zero-baseline shown in Fig. 5 are consistent with the error budget shown in Fig. 6. in summary, Fig. 6 represents a fairly conservative range of relative clock estimate errors which can be anticipated from the high-accuracy GPS estimation techniques used at J]'].

Fig. 6 implies a total GPS measurement noise contribution Of about 2x 10^{-15} at 100,000 sec. The observed Allan deviations in Fig. 4, which include noise from both the masers and the GPS measurements, are between 4x 10^{-15} and 9x 10^{-15} at 100,000 sec. These higher observed variations may be due to either the actual maser stabilities in the field, or to GPS system errors which are not fully accounted for in the error bud.yet.

It is possible that using a global ensemble clock Of H-masers connected by GPS time transfer would provide a more stable reference clock to use for comparisons with individual frequency standards whose noise characteristics are being probed. This concept is initially explored in a paper by Young, et. al., also presented in these proceedings.

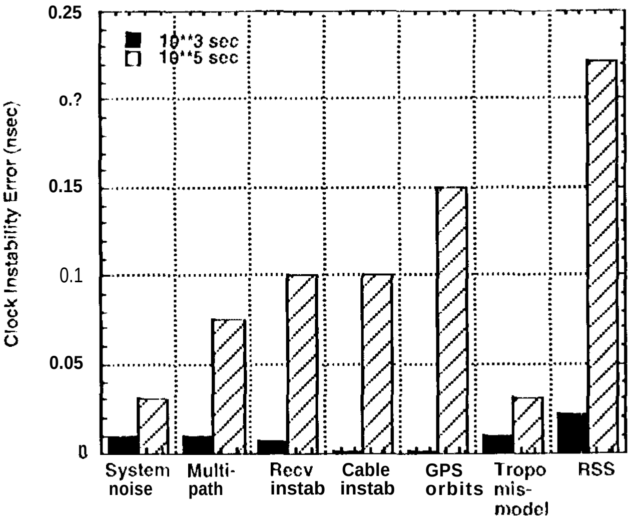

Figure 6: Error breakdown calculated for GPS relative clock measurements.

CONCLUSION

It has been shown that, with our current estimation strategies and models, precision GPS techniques can be used to achieve clock calibration at well below the nanosecond level. The GPS techniques described in this paper therefore have the potential to monitor actual long-term field performance of hydrogen masers (and other frequency standards). Future work will focus on further improvement of the precision of the GPS clock estimation methods, and on better separation of noise contributions from the GPS measurement technique versus noise effects in the precise time standards themselves.

ACKNOWLEDGMENT

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