Sub-Nanosecond Clock Synchronization* and Precision Deep Space Tracking

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Abstract

Interferometric spacecraft tracking is accomplished by the NASA Deep Space Network (DSN) by comparing the arrival time of electromagnetic spacecraft signals at ground antennas separated by baselines on the order of 8000 km. Clock synchronization errors within and between DSN stations directly impact the attainable tracking accuracy, with a 0.3 ns error in clock sync resulting in an 11 nrad angular position error . This level of synchronization is currently achieved by observing a quasar which is angularly close to the spacecraft just after the spacecraft observations. By determining the differential arrival times of the random quasar signal at the stations, clock synchronization and propagation delays within the atmosphere and within the DSN stations are calibrated. Recent developments in time transfer techniques may allow medium accuracy (50-100 nrad) spacecraft observations without near-simultaneous quasar-based calibrations. Solutions are presented for a global network of GPS receivers in which the formal errors in clock offset parameters are less than 0.5 ns. Comparisons of clock rate offsets derived from GPS measurements and from very long baseline interferometry and the examination of clock closure suggest that these formal errors are a realistic measure of GPS-based clock offset precision and accuracy.

Incorporating GPS-based clock synchronization measurements into a spacecraft differential ranging system would allow tracking without near-simultaneous quasar observations. The impact on individual spacecraft navigation error sources due to elimination of quasar-based calibrations is presented. System implementation, including calibration of station electronic delays, is discussed.

1. Introduction

NASA's Deep Space Network (DSN) supports spacecraft navigation for an international community of users. In order to complete most missions successfully, the location of the spacecraft must be determined with very high accuracy. This is done by comparing the arrival time of a signal broadcast by the spacecraft as it is received at two widely separated DSN stations. The delay observable thus formed provides some of the data from which the spacecraft's orbit is determined.

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Most of the observed time delay between two stations is due to the geometry of the spacecraft and receiving stations; however, delays due to solar plasma, the atmosphere of the earth, ground station instrumentation, and general relativity also play a role. This measurement technique is shown in Figure 1 and is called very long baseline interferometry (VLBI). In order to determine the angle, Θ, giving the direction to the spacecraft to an accuracy of $\delta\Theta$, the error in determining the delay, δt, can be no more than:

$$\delta t \leq \frac{D}{c}\delta\Theta \tag{1}$$

where D is the separation of the stations and c is the speed of light. Clearly, it is advantageous to use the longest baselines possible. Currently there are three DSN complexes at Goldstone, California; Madrid, Spain; and Canberra, Australia. Thus, a typical DSN baseline is 8000 km. A typical medium-accuracy tracking requirement is 50 nrad. Using equation (1) we arrive at a maximum error of 1.33 ns. In order to keep the total error in delay within this limit, the effective VLBI clock synchronization must be much better than 1 ns. Sub-nanosecond time transfer is a difficult problem, yet 50 nrad accuracy of spacecraft angular position in the radio reference frame is routinely obtained, and 5 nrad accuracy is achieved in special cases. This high level of performance is accomplished by using the signals from an extra-galactic radio source (quasar) to calibrate spacecraft observations. The radio signal from the quasar is essentially wide-band random noise, so when the recorded signals from the two stations are cross-correlated, significant correlation amplitude arises only when the quasar delay is precisely matched. This has the effect of measuring the station clock offset as well as differencing out many of the errors which are common to the quasar and spacecraft observations. The spacecraft signal spectrum contains tones which are used to measure a one-way range from the spacecraft to the earth station. An observable formed by subtracting the quasar delay from the spacecraft one way range, difference between stations, determines one component of the geocentric angle between the spacecraft and quasar. Measurements must be made on two baselines to determine both components of angular position.

An error budget for spacecraft-quasar differential VLBI delay measurements is given in Table 1. This error estimate is based on expected DSN receiver performance and calibration systems capabilities in the late 1990's. [4]. The root-sum-square error is 0.22 ns. By contrast, systems operating today provide an accuracy of about 0.67 ns. **[3]**.

Error Source	Magnitude (ns)
Quasar SNR	0.11
Spacecraft SNR	0.033
Quasar Position	0.066
Clock Offset	0.030
Phase Ripple	0.10
Station Location	0.033
Earth Orientation	0.056
Troposphere	0.080
Ionosphere	0.010
Solar Plasma	0.017
RSS:	0.22

Table I: Spacecraft–Quasar differential VLBI error budget

Although this method provides accuracy sufficient to carry out deep space missions, it has some drawbacks. In order to be useful, the quasar observations must be made as close in time as possible to the spacecraft observations. In order to view the quasar, the antenna must be physically pointed at the quasar and is unable to receive signals from the spacecraft. As a result, the phase data from the spacecraft is not continuous, which results in a weaker orbit solution and a gap in spacecraft telemetry while the quasar is being observed.

Quasar observations also complicate the hardware otherwise required to track a spacecraft. The quasar is a wideband radio source, and so a wide bandwidth is required to record and process the quasar data. If the quasar could be dispensed with, only the phases of the received spacecraft signals at each time point would need to be recorded. In the quasar-less system proposed here, 50 nrad observables could be available in near-real-time. The number of bits resulting from spacecraft tracking would be reduced from 10^9 to 10^5.In this paper, we will examine medium-accuracy deep space tracking as an application of sub-nanosecond clock synchronization. We will begin by defining the requirements 50 nrad tracking accuracy places on the clock synchronization system. We will then discuss recent results obtained using the U. S. Global Positioning System (GPS) satellites for clock synchronization which indicate this level of accuracy may be possible on an operational basis. Finally, we will discuss the hurdles remaining before this technology can be implemented.

2. Clock Synchronization Requirements

Time-transfer aided spacecraft tracking will never be able to achieve the accuracy possible using quasar-based differential VLBI. This is because in differencing the quasar signals, many of the media errors affecting the signal are differenced out as well. Without quasar differencing, the errors due to station location, earth orientation, troposphere and ionosphere would increase by a factor of 2 to 4. The GPS solution from which the VLBI clock offset will be derived can also be used to provide calibrations for earth orientation and troposphere and ionosphere delays. We will assume that these errors increase by a factor of three compared to quasar calibrated VLBI. Of the remaining errors, those pertaining to quasar SNR and quasar location are eliminated with the elimination of the quasar. The errors due to spacecraft SNR, phase ripple, and solar plasma would remain unchanged. If GPS is used to estimate clock offsets every six minutes during the spacecraft pass, the clock instability error remains roughly the same. The RSS of all errors excluding the clock is 0.534 ns. This leaves 1.2 ns maximum allowable clock synchronization error, which includes instrumental errors incurred in tying GPS time to VLBI time. A reasonable system allocation is 0.5 ns for clock synchronization errors.

3. Achieving Sub-Nanosecond Clock Synchronization

Since the inception of the Global Positioning System in 1978, the possibility of using it for high accuracy clock synchronization has matured rapidly. The number of GPS satellites has recently reached 16, and, in addition, capable p-code receivers have proliferated. For this reason, the possibility of achieving ns and better clock synchronization using the GPS system has been studied **[5,1,9,16,6]**.

In order to investigate the feasibility of meeting the requirements posed in section 2, the authors investigated clock offset solutions for a global network of Rogue **[10]** GPS receivers which was assembled for the IERS GIG-'91 campaign in January and February of 1991 **[11]**. Clock offsets were calculated for the three DSN sites and compared with clock data derived from VLBI quasar measurements. A closure measurement was made to verify the internal consistency of the method.

3a. Comparison With VLBI

The GIG-'91 data from the 21 global Rogue sites were processed with the Jet Propulsion Laboratory's GIPSY software. A general description of the square-root Kalman filtering algorithms used for determination of timing and geodynamical parameters simultaneously along with GPS orbits is described in detail by Lichten [**7,8, and references therein**]. Estimated parameters included: GPS positions and velocities, three solar pressure coefficients per satellite, GPS carrier phase biases, non-fiducial station coordinates, variations in Earth rotation (UT1-UTC), random walk zenith troposphere delays for each site, and white noise transmitter/receiver clocks. The only significant constraint imposed on the estimated parameters was the random walk constraint for the tropospheric delay, $1.2\mathrm{cm}/\sqrt{hr}$ (the random walk model adds process noise to the system such that in the absence of data, the uncertainty for the parameter increases as the square-root of time). All other estimated parameters, including the clocks, were essentially unconstrained. The white noise [**8,2**] clock model for the station and satellite clocks corresponds to estimation of a new and independent clock offset for each receiver/transmitter (one ground clock was held fixed as reference for all the other clocks in the system) at each measurement time (every six minutes in this case). This approach is very conservative, since most of the GPS clocks and many of the receiver clocks were running off atomic standards (high quality hydrogen masers for the three Deep Space Network sites) and it would be quite reasonable to apply constraints based on known stable behavior of such clocks. However, we wished to test the capability of GPS to independently and completely characterize all the clocks in the system without *a priori* knowledge and therefore used the white noise model. Coordinates for two fiducial sites, Goldstone (California) and Kootwijk (Netherlands), were held fixed (not estimated) to their SV5 values. SV5 is a reference frame defined primarily by VLBI measurements of baselines and satellite laser ranging determination of the geocenter [**12**]. Three geocenter parameters were also estimated, representing a translation estimated from the GPS data for the Earth center of mass relative to the nominal SV5 origin. The GPS data were initially filtered in 24-hr increments, with new solutions for the orbits determined for each day. Since the computed formal errors for the estimated clock offsets appeared to be well below 1 ns (typically several tenths of ns), in some cases we used 12-hr solution arcs in order to shorten the processing time.

The nominal time series for both polar motion and UT1-UTC was from the International Earth Rotation Service (IERS) Bulletins B37 and B38, which contain a smoothed time series from VLBI measurements separated by 5 days. The GPS data were used to estimate variations in UT1-UTC twice per day relative to this nominal time series. These Earth rotation estimates had only an insignificant effect on the clock estimates. In order to tie GPS data to the DSN station clocks, the Rogue GPS receiver was fed a 5 MHz reference signal generated by the station hydrogen maser frequency standard. The time tags of the data are derived from this reference, subject to delays within the interconnection and the receiver. The highly digital nature of the Rogue receiver eliminates most of the delay variations which arise from variability of analog components [**14**]. The remaining receiver instrumental delays have been shown to remain constant on a day-to-day basis to within 0.7 ns [**17**]. This insures that the receiver clock and the station clock run at the same rate within $\sim .7$ ns/day.

Currently there exists no system to measure the offset between the station clock and the receiver clock. As a result, we assume a constant offset and compare clock rates derived from GPS with those derived from VLBI. This problem will be discussed further in section 4.

For this experiment, GPS selective availability (SA) was not turned on. Because the measurements involve only differenced data involving many receivers and satellites with dynamically estimated orbits and spacecraft clocks, this technique is insensitive to SA. This statement is based on our limited experience from the past two years. When SA was active, the accuracy and precision of ground station position estimates were insensitive to SA. If the p-code is encrypted with anti-spoofing (AS), however, our results would be somewhat degraded. Because the Rogue receiver is able to extract ionospheric TEC by cross- correlating the P1 and P2 signals, however, even in the event of AS we expect to maintain sub-nanosecond clock synchronization.

Date (1991)	**Baseline**	**VLBI** (ns/day)		**GPS** (ns/day)	
Jan 23	Canberra–Goldstone	-10.0	±1.6	-9.0	±0.9
Jan 27	Madrid–Goldstone	-4.5	±2.2	-2.7	±0.5
Jan 30	Canberra Goldstone	-7.9	±3.1	-9.1	±0.9
Feb 06	Canberra–Goldstone	46.6	±1.3	46.4	±1.9
Feb 10	Madrid–Goldstone	5.9	±1.8	2.8	±0.4

Table 2: Clock rate estimates

Table 2 presents a comparison of the GPS clock rates with VLBI clock rates on days when VLBI solutions were available (GPS solutions were available nearly continuously during the 3-week experiment). The column labelled "VLBI" presents the clock frequency offset between the specified DSN sites as determined by the DSN TEMPO **[13]** service. These measurements are made by observing a set of quasars over a three hour interval centered on the listed time tag. The column labelled "GPS" was produced by decimating clock estimates originally computed at a 6-min minute interval to a 60-min interval and then fitting six or seven of these points to a line. The hourly points are selected to be centered as closely as possible on the VLBI time tag. An example of one of these fits is shown in Graph 1. The typical RMS scatter in these GPS clock fits was 0.1- 0.3 ns.

VLBI is probably the most accurate established independent technique for measuring clock differences between tracking sites separated by intercontinental distances. Yet the formal errors for the GPS fits are similar, and in most cases, lower than the VLBI formal errors. The reduced χ^2 statistic for the GPS fits, which basically measures the ratio of the post-fit scatter to the formal clock estimate errors, was generally 0.5-1.0. The agreement between the GPS and VLBI clock rate estimates shown above in the table is at the $\sim$ ns/day level and can in all except one case be explained by the VLBI formal errors in estimating the clock rates (the one exception on Feb 10 shows a difference of about 1.5 VLBI standard deviations). Note that some aspects of our conservative GPS fitting procedure (decimation of data by a factor of 30, and fitting a line to the clock offset time series instead of solving explicitly for the rate parameter with the original data) tend to make the GPS formal errors (and presumably the actual errors) larger. A more aggressive analysis strategy could easily be devised to further reduce the GPS clock rate estimation errors. The results suggest, in any case, that the GPS observations can be straightforwardly used to faithfully track clock variations at time and frequency standards separated by thousands of km. Our comparison with the independent VLBI technique appears to be limited by the uncertainties in the VLBI data, not by uncertainties in the GPS data.

3b. Clock Closure

To investigate the internal consistency of our estimates, we chose a typical day (February 2) and estimated the clock offset between each pair of DSN stations with the data from the remaining station excluded for a twelve hour period. The sum of these numbers was then formed, which we refer to as the clock closure. If the receiver clocks have the same estimate in each of the runs, the clock closure will be zero. The clock closure is shown as a function of time in Graph 2. The formal errors presented are calculated assuming each of the six estimates has an independent random error, summed in quadrature, and are thus probably on the conservative side.

Removing the data from a single station should have a very small effect on the result. Non- zero clock closure is an indication of systematic errors in the calculation of the offset of the remaining two clocks. By examining the clock closure, we hope to identify error sources as well as verify that nothing is seriously wrong with our estimates.

The curve in Graph 2 has several interesting features. We believe the large, slow, variation in the clock closure result is due to errors in our estimated GPS satellite orbits. To test this, we initialized the orbital parameters with values estimated from data collected in the previous 24 hour period, including all stations. The resulting clock closure is shown in Graph 3. The large scale variation is absent, although it has been replaced with a 0.2 ns bias. This can be explained because the orbits are constrained by the previous 24 hours of data and therefore are less sensitive to data noise. On the other hand, systematic orbit errors due to dynamic models are more important for longer data arcs and may be causing the 0.2 ns bias.

Another of these features is the small (0.1 ns) jump occurring just before 2 am on Graph 2. We believe this is due to an abrupt change in the satellite geometry, with most satellites either rising or setting, as can be inferred from the change in size of the formal error bars. The step seen at 2 am is an indication of an error in clock determination due to poor sattelite geometry before 2 and the short data arcs resulting from sattelites setting. The jump near noon appears to be due to similar satellite geometry problems, as well as a short data outage.

The GPS constellation in early 1991 consisted of only 15 operational satellites. There are short periods of time when GPS visibility is poor from a given ground site, thus leading to high sensitivity to scheduling of observations and data gaps such as described above. We expect that in the future, with the fully operational 21-satellite constellation, such events would cause less error.

In another test for data consistency, we changed the reference clock. For Jan. 23, we compared the clock solutions with Goldstone the reference clock and with Kokee (Hawaii) the reference clock. Because both clocks were hydrogen masers, no appreciable difference in solutions should occur. The clock rate solutions differed by 0.03 ns/day and 0.01 ns/day respectively for the two cases, a statistically insignificant difference.

3c. Data Availability

Another important issue to be addressed is whether high quality GPS clock estimates can be produced reliably enough to be used operationally. During the IERS GIG-91 campaign, it was possible to form a clock offset with formal errors less than 1 ns for 74% of the hourly estimates on the Goldstone-Madrid baseline and 79% of the time on the Goldstone- Canberra baseline. This includes times in which there was insufficient common view to obtain an accurate clock offset, as well as periods in which one of the two receivers was not tracking satellites.

With the full 21-satellite GPS constellation and with data from approximately six to nine globally distributed stations in addition to the DSN stations, it should be possible to continuously provide sub-nanosecond clock offset estimates for the DSN complexes. It is currently possible to service such a network and provide one day turnaround of clock estimates [personal communication; G. Blewett]. With the development of forward-running Kalman filters and a real-time data-retrieval system, it would conceivably be possible to provide one ns, hydrogen maser, clock offsets in as little as 5 minutes. Somewhat better offsets could be provided within a few hours. More study is needed to determine the minimal configuration necessary to provide near-real-time clock estimates. Note that because the DSN stations are equipped with hydrogen masers, errors in estimated clock offsets grow gradually, so that short GPS data outages are more likely to result in degraded system performance rather than catastrophic system failure.

4. Implementation

In order to implement an operational GPS-aided VLBI system, the receiver clock synchronization discussed above must be transferred to the VLBI clock. This can be done by using a time interval counter (TIC) to measure the difference in the 1 pps signals generated by Rogue and VLBI time. It is not difficult to obtain time interval counters accurate to 100 psec, which would not severely impact our level of accuracy. This TIC would be machine readable to allow real-time calibration at a rate similar to the frequency of clock offset estimates available from the GPS solution.

The calculated clock offset between receiver time and GPS time includes the delays and phase shifts introduced by the analog electronics between the GPS antenna and the Rogue receiver. The only remaining uncalibrated delays are between internal receiver time and the resultant 1 pps signal, and the corresponding delay in the VLBI system. JPL experiments have shown that these combined delays in the receiver remain constant over four days period to within 0.3 to 0.7 ns [**17**]. These delays can be calibrated by making quasar VLBI observations and comparing the clock synchronizations determined by this method with GPS clock synchronization. Two-way satellite time transfer is also approaching the accuracy necessary to calibrate GPS instrumental errors. Quasar observations are currently performed weekly on each baseline to determine earth orientation and clock offsets and rates. If receiver delays can be held constant to within the 0.5 ns limit given in section 2, it appears that instrumental errors in GPS clock synchronization can be dealt with by weekly quasar calibration. If this is not possible, two-way satellite time transfers on a more frequent basis may be necessary.

5. Conclusion

A sub-nanosecond clock synchronization capability would be of great benefit to deep space tracking. This level of synchronization would allow spacecraft angular position to be instantaneously measured to an accuracy of 50 nrad by differential ranging at two widely separated tracking stations. Quasar-based differential VLBI, which is currently used for this purpose, might be reserved for only the most demanding navigation challenges. Clock offsets between DSN stations with formal errors of approximately 0.5 ns have been determined from GPS measurements. Comparisons of VLBI and GPS clock rates and analysis of clock closure suggest that these formal errors are a realistic measure of the precision of the GPS clock solutions. The calibration of absolute station instrumental delays and of the offset between VLBI time (used to time-tag differential spacecraft range measurements) and GPS receiver time appear to be tractable implementation tasks.

Acknowledgment

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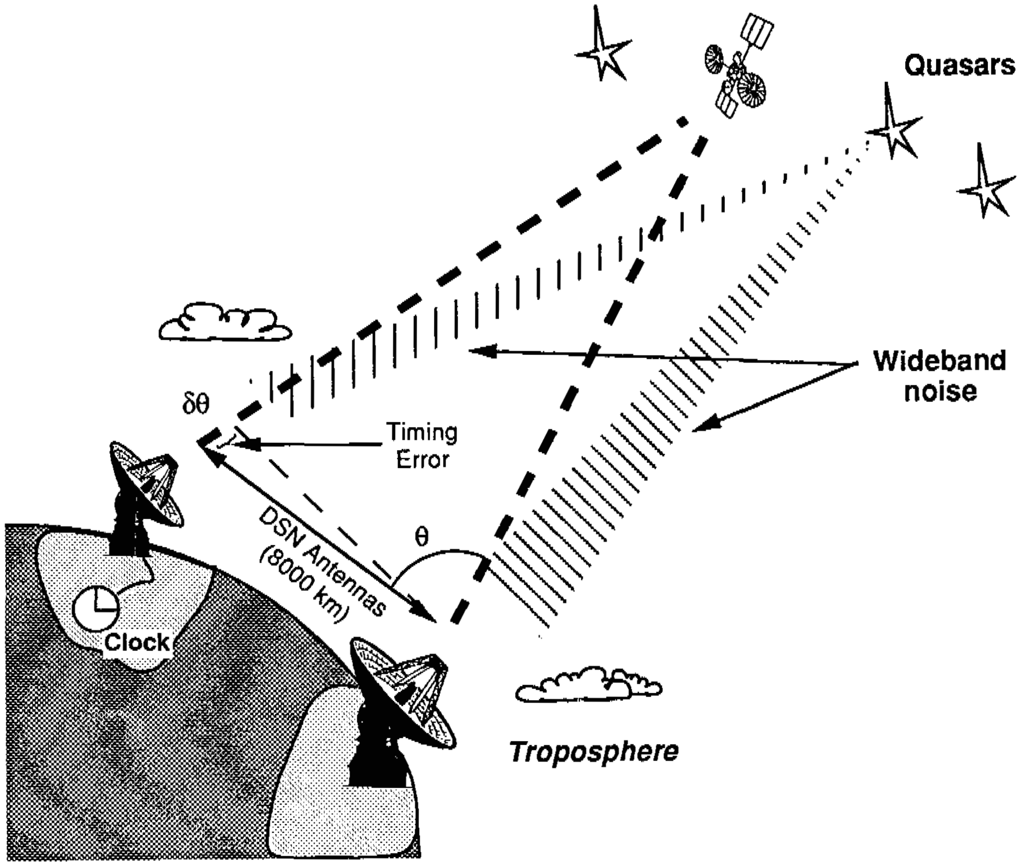
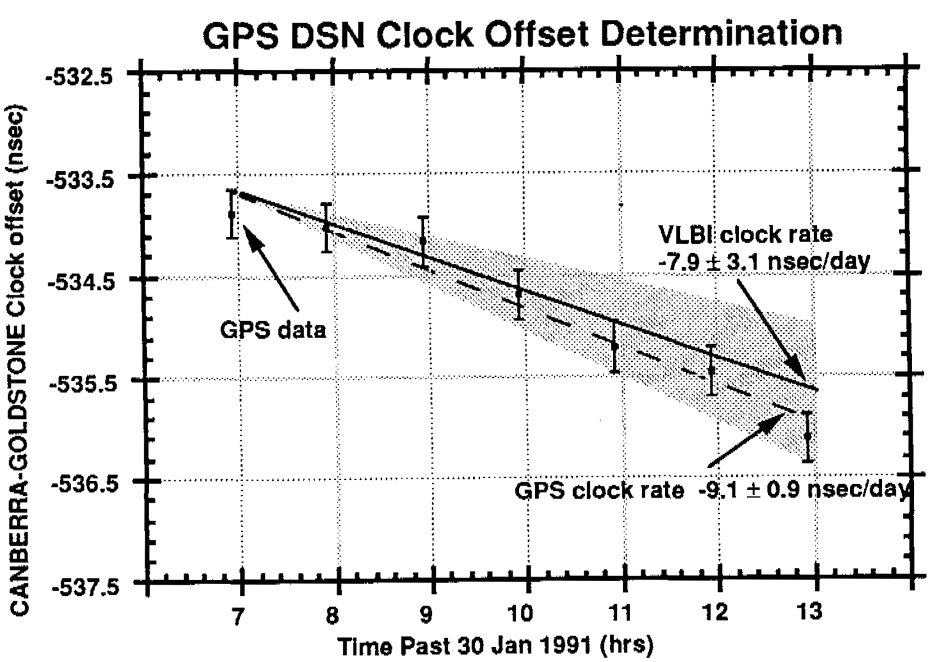
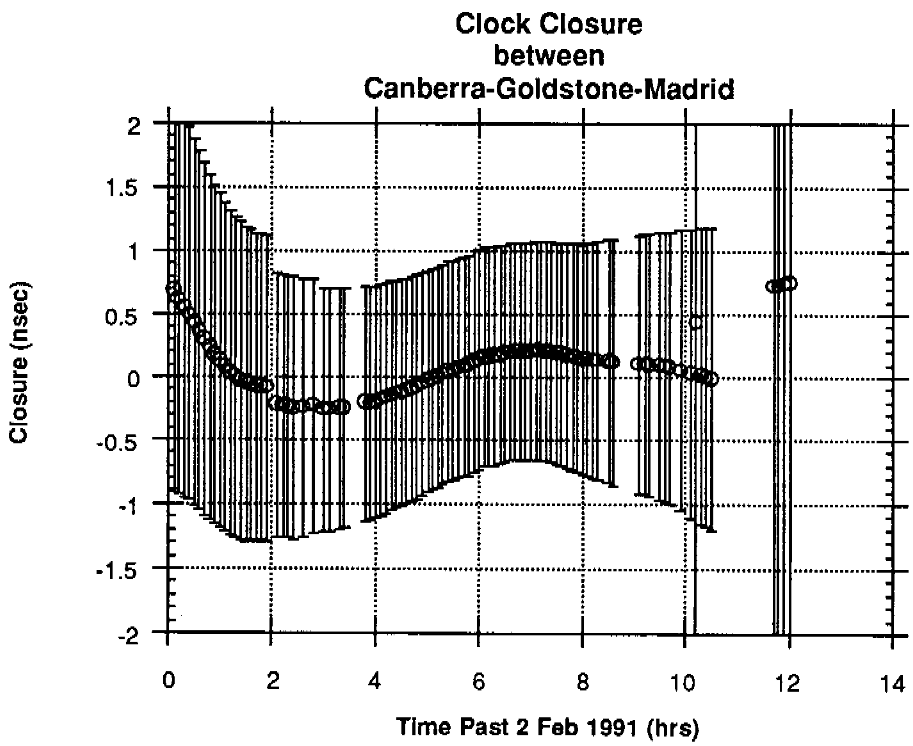


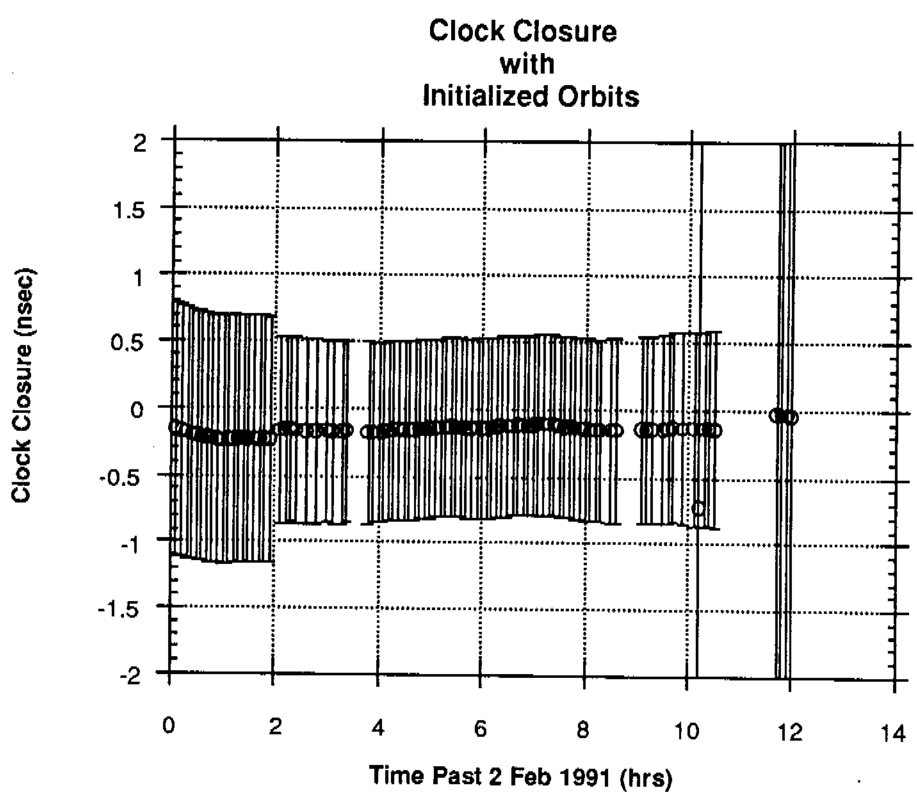
Figure 1: Quasar differenced VLBI spacecraft tracking.



Graph 1: Comparison of GPS and VLBI derived clock offset estimates.



Graph 2: Clock closure with dynamically determined orbits.



Graph 3: Clock closure with orbits initialized from previous day.

QUESTIONS AND ANSWERS

Dr. Gernot Winkler, USNO: Your results are outstanding. What is the reason for that. Your orbit determinations appear to be much better than anything else that I have seen. Have you had an opportunity to compare your orbits *ex post facto* with DMA or NGS orbits?

Mr. Border: I am not an expert on the orbits. If you care to talk to me afterwards, I can give you some names of people that could give you better information. I know that, within our section, we believe the orbits are good to 50 nanoseconds. That comes from comparing with baselines from VLBI, daily repeatabilities, and comparisons of our orbits with other peoples orbits.

Dr. Winkler: You must also have a better signal-to-noise in your receivers. Which antennas are you using?

Mr. Border: We are using ROGUE Receivers with Dorne-Margolin (sp?) antennas. The receivers are highly digital receivers, so they produce high quality data with very few cycle slips.

Mark Weiss, NIST: I am curious about the feasibility of using techniques like this for time transfer in a near-real-time mode. Even a week after fact would be useful. I am wondering about cycle slips, does the GYPSY software automatically detect and correct for cycle slips?

Mr. Border: GYPSY software automatically handles cycle slips and things like that. With ROGUE receivers, cycle slips are not generally a very significant problem. The strategy that I presented here was the standard estimation strategy used for geodetic measurements. GYPSY handles orbits, cycle slips and things like that. The other question that you asked was about near-real-time results. More software development will be needed to develop a forward-running filter, so that we can incorporate data as it arrives. Right now we have about a days turn around on our numbers. Reducing that is one of the future goals.

Mr. Weiss: So you are saying that we can do time transfer at the sub-nanosecond leave using ROGUE receivers, with a days turn-around.

Mr. Dunn: Yes, that is what I am saying.

Mr. Weiss: But we would have to have ROGUE receivers spread around the world to be able to do the orbits.

Mr. Dunn: Certainly to duplicate our results. We are using 21 receivers around the world, but we think that is overkill for doing time transfer. You would need a number of sites.

G. Petit, BIPM: Is your processing with the GYPSY software with all the satellites all the time?

Mr. Dunn: It is with all satellites, all the time. For a given estimate, the clocks necessarily close. In order to produce clock offset estimates that don't necessarily close, we remove the data from one of the DSN stations and produce a clock offset estimate for the remaining two. We do this three times, for the different stations, and sum the offsets. Because most of the stations are still in, we expect the errors to be highly correlated. As a result, this is probably an underestimate of our total error. This particular closure method is a good diagnostic tool in terms of seeing what magnitude of effect we can expect from orbit error. However, I would like to point out that, when people use broadcast ephemerides, they are essentially using correlated information, so those clock closure measurements have a very similar interpretation.

David Allan, NIST: I have two questions. First, on the same chart, do have any explanation about the steps in the data near the end, and second, what do you do about SA?

Mr. Dunn: There were a number of satellites that rose and set about the same time and also some of the equipment was turned off at that time. We aren't entirely sure what caused the step. The large errors near the ends of the run are due to the fact that, for this data set, we used 12 hour data arcs to reduce the processing time. When a satellite rises near the end of the arc or sets near the beginning of the arc, then you have fairly low data weight for that satellite. As a result, you can see that the formal errors blow up quite a bit. In routine processing this will be less of an issue, since there will be more satellites in the constellation and we will be able to run over longer periods. In geodetic work, we have found that we are fairly insensitive to SA. You can see the effect in the results, however it is very small. We believe that this is due to the fact that these measurements are essentially a differenced data type. We solve for all of the clocks at each epoch and so SA should tend to difference out. AS, on the other hand, could be a significant problem.