Subnanosecond GPS-Based Clock Synchronization and Precision Deep-Space Tracking

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Interferometric spacecraft tracking is accomplished by the 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-nsec error in clock synchronization 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 offsets 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 tracking without near-simultaneous quasar-based calibrations. Solutions are presented for a worldwide network of Global Positioning System (GPS) receivers in which the formal errors for DSN clock offset parameters are less than 0.5 nsec. Comparisons of clock rate offsets derived from GPS measurements and from very long baseline interferometry, as well as 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.

I. Introduction

The 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.

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 Fig. 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

$$\delta t \leq \frac{D}{c}\delta\theta \qquad (1)$$

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 Eq. (1), one arrives at a maximum error of 1.33 nsec.

In order to keep the total error in delay within this limit, the effective VLBI clock synchronization must be better than 1 nsec. Subnanosecond 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 extragalactic radio source (quasar) to calibrate spacecraft observations. The radio signal from the quasar is essentially wideband random noise, so when the recorded signals from the two stations are cross-correlated, significant correlation amplitude arises only when the differential quasar-to-station delay is precisely matched by the offset in tape playback times. 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 1990s [1]. The

root-sum-square error is 0.22 nsec. By contrast, systems operating today provide an accuracy of about 0.67 nsec.[1]

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 thus unable to receive signals from the spacecraft. As a result, the phase data from the spacecraft are 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 quasarless system proposed here, 50-nrad observables could be available in near-real time. The number of bits resulting from a $\sim$10-min observation would be reduced from 10^9 to 10^5.

This article will examine medium-accuracy deep space tracking as an application of subnanosecond clock synchronization. It will begin by defining the requirements that 50-nrad tracking accuracy places on the clock synchronization system. It will then discuss recent results obtained using Global Positioning System (GPS) satellites for clock synchronization, which indicate this level of accuracy may be possible on an operational basis. Finally, it will discuss the hurdles remaining before this technology can be implemented.

II. 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. However, 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

[1] J. S. Border, *Analysis of DDOR and DDOD Measurement Errors for Mars Observer Using the DSN Narrow Channel Bandwidth VLBI System*, JPL Interoffice Memorandum 335.1-90-026 (internal document), Jet Propulsion Laboratory, Pasadena, California, 1990.

delays. A conservative assumption is that these errors increase by a factor of 3 compared to quasar-calibrated VLBI. Of the remaining errors, those pertaining to quasar signal-to-noise ratio (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 6 min during the spacecraft pass, the clock instability error remains roughly the same. The rss of all errors excluding the clock is 0.534 nsec. This leaves a 1.2-nsec maximum-allowable clock synchronization error, which includes instrumental errors incurred in tying GPS time to VLBI time. A reasonable and conservative system allocation is 0.5 nsec for clock synchronization errors, which would allow for a margin of safety of about a factor of 2.

III. Achieving Subnanosecond Clock Synchronization

Since the inception of the GPS in 1978, techniques for using it for high-accuracy clock synchronization have 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 nsec and better clock synchronization using the GPS system has been studied [2–6].

In order to investigate the feasibility of meeting the requirements posed in Section II, the authors investigated clock offset solutions for a global network of Rogue [7] GPS receivers which was assembled for the GPS International Earth Rotation Service (IERS) and Geodynamics (GIG'91) campaign in January and February of 1991 [8]. Clock offsets were calculated for the three DSN sites and compared with clock data derived from VLBI quasar measurements. A closure test was made to verify the internal consistency of the method.

A. Comparison With VLBI

The GIG'91 data from the 21 global Rogue sites were processed with the Jet Propulsion Laboratory's GPS Inferred Positioning System (GIPSY) software. A general description of the square-root Kalman filtering algorithms used for determination of timing and geodynamical parameters simultaneously with GPS orbits is described in detail in [9,10] and references therein. Estimated parameters included GPS positions and velocities, three solar pressure coefficients per satellite, GPS carrier phase biases, nonfiducial station coordinates, variations in Earth rotation (UT1–UTC), random-walk zenith troposphere delays for each site, and white-noise transmitter and receiver clocks. The only significant constraint imposed on the estimated

parameters was the random-walk constraint for the tropospheric delay, 1.2 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 [10,11] clock model for the station and satellite clocks corresponds to the estimation of a new and independent clock offset for each receiver and transmitter (one ground clock was held fixed as a reference for all the other clocks in the system) at each measurement time (every 6 min 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 DSN sites), and it would be quite reasonable to apply constraints based on known stable behavior of such clocks. However, the authors wished to test the capability of the 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's 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 nsec (typically several tenths of a nsec), in some cases 12-hr solution arcs were used 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 [13,14], 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 [15]. The remaining receiver instrumental delays have been shown to remain constant on a day-to-day basis to within 0.7 nsec.[2] This insures that the receiver clock and the station clock run at the same rate within ~0.7 nsec/day.

Currently there exists no system to measure the offset between the station clock and the receiver clock. As a result, a constant offset is assumed and clock rates derived from GPS are compared with those derived from VLBI. This problem will be discussed further in Section IV.

For this experiment, GPS selective availability (SA) was not turned on. SA involves a dithering of the GPS frequencies, which has the effect of making the GPS clocks look very noisy to users who are not authorized with the classified keys. When SA is on, the GPS broadcast information about GPS clocks and ephemerides is also altered to degrade the accuracy of point positioning by users without the keys. However, since the GPS estimates in this experiment involve only simultaneous data involving many receivers and satellites with dynamically estimated orbits and spacecraft clocks, this type of GPS processing is insensitive to both components (dithering and broadcast ephemerides) of SA. The estimated GPS clocks and orbits remove the SA effects, while the ground (DSN) clock estimates are unaffected. This statement is supported by the authors' limited experience from the past two years. When SA was active, the accuracy and precision of ground-station position estimates were insensitive to SA. A second type of GPS user restriction can result from antispoofing (AS), which encrypts the p-code with a Y-code that can be used directly only by certain authorized users. By effectively restricting most users to single (L1) frequency operation, antispoofing can degrade the accuracy of some GPS measurements. If the p-code were so encrypted, these results would probably be somewhat noisier. However, the Rogue GPS receiver is still able to provide an ionospheric calibration by cross-correlating the P1 and P2 signals. Hence, even in the event of AS, the authors expect to maintain subnanosecond clock synchronization.

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 VLBI column presents the clock frequency offset between the specified DSN sites as determined by the DSN Time and Earth Motion Precision Observations (TEMPO) [16] service. These

measurements are made by observing a set of quasars over a 3-hr interval centered on an epoch. The GPS column was produced by decimating clock estimates originally computed at a 6-min interval to a 60-min interval and then fitting 6 or 7 of these points to a line. The hourly points are selected to be centered as closely as possible on the VLBI epoch. An example of one of these fits is shown in Fig. 2. The typical rms scatter in these GPS clock fits was 0.1–0.3 nsec.

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 postfit scatter to the formal clock estimate errors, was generally 0.5–1.0. The agreement between the GPS and VLBI clock rate estimates shown in Table 2 is at the ~nsec/day level and can be explained by the VLBI formal errors in estimating the clock rates. Note that some aspects of the 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. The comparison made by the authors with the independent VLBI technique appears to be limited by the uncertainties in the VLBI data, not by uncertainties in the GPS data.

B. Clock Closure

To investigate the internal consistency of the estimates, a typical day (February 2, 1991) was chosen, and the clock offset between each pair of DSN stations was estimated, with the data from the remaining station excluded for a 12-hr period. The sum of these numbers was then formed, which is referred to as the clock closure. If the receiver clocks have the same estimate in each of the runs for which they are included, the clock closure will be zero. The clock closure is shown as a function of time in Fig. 3. 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. Nonzero clock closure

is an indication of systematic errors in the calculation of the offset of the remaining two clocks. By examining the clock closure, the authors hope to identify error sources as well as verify that nothing is seriously wrong with their estimates.

The curve in Fig. 3 has several interesting features. It is believed that the large, slow variation in the clock-closure result is due to errors in the estimated GPS satellite orbits. To test this, the orbital parameters were initialized with more precise values by using data collected in the previous 24-hr period, including all stations. The resulting clock closure is shown in Fig. 4. The large-scale variation is absent, although it has been replaced with a 0.2-nsec bias. This can be explained because the orbits are constrained by the previous 24 hr 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-nsec bias.

Another of these features is the small (0.1-nsec) jump occurring just before 2:00 a.m., as shown in Fig. 3. This is thought to be due to an abrupt change in the satellite geometry, since relatively few satellites were visible at that time and most were either rising or setting. The jump near noon may be due to similar satellite geometry effects, as well as a short data outage. The GPS constellation in early 1991 consisted of only 15 operational satellites. There were short periods of time when GPS visibility was poor from a given ground site, thus leading to high sensitivity to scheduling of observations and data gaps such as described above. It is expected that, in the future, complete ground coverage with the fully operational 21-satellite constellation will make such episodes infrequent and of less consequence.

In another test for data consistency, the reference clock was changed. For January 23, 1991, the clock solutions with Goldstone, California, as the reference clock were compared with the solutions with Kokee, Hawaii, as the reference clock. Because both clocks were hydrogen masers, no appreciable difference in solutions should occur. The clock rate solutions differed by 0.03 nsec/day and 0.01 nsec/day, respectively, for the two cases, a statistically insignificant difference.

C. 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 of less than 1 nsec for 74 percent of the hourly estimates on the Goldstone–Madrid baseline and 79 percent 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 subnanosecond clock-offset estimates for the DSN complexes. It is currently possible to service such a network and provide one-day turnaround of clock estimates.[3] For example, with recently installed Hewlett Packard computers in the supermini class, full filtering and smoothing for 24 hr of GPS data from a global tracking network require approximately 1 hr of computing time, including computation of postfit data residuals, some data editing, and automated outlier removal and correction. With the development of forward-running Kalman filters and a real-time data-retrieval system, it conceivably would be possible to provide 1-nsec, hydrogen-maser clock offsets in as little as 5 min by incrementally adding small amounts of data to a continuously running Kalman filter. 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.

IV. 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-pulse-per-second (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 the level of accuracy. This TIC could be

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[3] G. Blewitt, personal communication, Technical Group Supervisor, Tracking Systems and Applications Section, Jet Propulsion Laboratory, Pasadena, California, November 1, 1991.

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 a 4-day period to within 0.3 to 0.7 nsec.[4] These delays can be calibrated by making occasional 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-nsec limit given in Section II, 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.

V. Conclusion

A subnanosecond clock synchronization capability would be of great benefit to deep space tracking. This level of synchronization would allow spacecraft angular position to be measured to an accuracy of 50 nrad by differential ranging at two widely separated tracking stations with the potential for near-real-time capability. 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 nsec 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.

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[4] L. E. Young, op. cit.

Acknowledgments

References

[1] J. S. Border and E. R. Kursinski, "Deep Space Tracking and Frequency Standards," *Proceedings of the 45th Annual Symposium on Frequency Control*, Los Angeles, California, pp. 594–607, May 29–31, 1991.

[2] L. A. Buennagel, D. J. Spitzmesser, and L. E. Young, "One Nanosecond Time Synchronization Using Series and GPS," *Proceedings of the 24th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, NASA Conference Publication 2265, Greenbelt, Maryland, pp. 605–620, December 1–2, 1982.

[3] D. W. Allen and M. Weiss, "Accurate Time and Frequency Transfer During Common-View of a GPS Satellite," *Proceedings of the 34th Annual Symposium on Frequency Control*, Philadelphia, Pennsylvania, pp. 334–346, 1980.

[4] W. Lewandowski, C. Petit, C. Thomas, and M. Weiss, "The Use of Precise Ephemerides, Ionospheric Data and Corrected Antenna Coordinates in a Long-Distance GPS Time Transfer," *Proceedings of the 22nd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*," NASA Conference Publication 3116, Vienna, Virginia, pp. 547–548, December 4–6, 1990.

[5] C. Veillet, D. Feraudy, J. M. Torre, J. F. Mangin, P. Gruder, F. Baumont, J. Gaignebet, J. L. Hatat, W. Hanson, A. Clements, J. Jesperson, M. Lombardi, D. Kirchner, H. Ressler, S. S. Fassi, W. J. Klepczynski, P. J. Wheeler, W. Powell, A. Davis, M. Granveaud, and D. Uhrich, "LASSO, Two-Way and GPS Time Comparisons: A (Very) Preliminary Status Report," *Proceedings of the 22nd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, NASA Conference Publication 3116, Vienna, Virginia, pp. 575–582, 1990.

[6] W. J. Klepczynski, M. Miranian, J. Jeffries, P. J. Wheeler, and W. Powell, "Comparison of Two-Way Satellite Time Transfers and GPS Common View Time Transfers," 43rd Annual Symposium on Frequency Control, Denver, Colorado, pp. 199–201, 1989.

[7] T. K. Meehan, T. Munson, J. Srinivasan, J. B. Thomas, L. E. Young, and R. Neilan, "ROGUE: A New High Accuracy Digital GPS Receiver," paper presented at the 19th General Assembly, Int. Union of Geod. and Geophys., Vancouver, Canada, August 9–22, 1987.

[8] W. G. Melbourne, S. S. Fisher, R. E. Neilan, T. T. Yunck, B. Engen, Ch. Reigber, and S. Patevjan, "The First GPS IERS and Geodynamics Experiment—1991," XX General Assembly International Union of Geodesy and Geophysics, Symposium G2.2, International Association of Geodesy, Vienna, Austria (in press), 1991.

[9] S. M. Lichten, "Towards GPS Orbit Accuracy of Tens of Centimeters," *Geophys. Res. Lett.*, vol. 17, pp. 215–218, 1990.

[10] S. M. Lichten, "Estimation and Filtering for High-Precision GPS Positioning Applications," *Manuscripta Geodaetica*, vol. 15, pp. 159–176, 1990.

[11] G. J. Bierman, *Factorization Methods for Discrete Sequential Estimation*, New York: Academic Press, 1977.

[12] M. H. Murray, R. W. King, and P. J. Morgan, "SV5: A Terrestrial Reference Frame for Monitoring Crustal Deformation with the Global Positioning System," 1990 Fall AGU Meeting, *EOS Trans. AGU*, vol. 71, p. 1274, 1990.

[13] *IERS Monthly Bulletin*, B37, IERS Central Bureau, Observatoire de Paris, Paris, France, 1991.

[14] *IERS Monthly Bulletin*, B38, IERS Central Bureau, Observatoire de Paris, Paris, France, 1991.

[15] J. B. Thomas, *Functional Description of Signal Processing in the Rogue GPS Receiver*, JPL Publication 88-15, Jet Propulsion Laboratory, Pasadena, California, June 1, 1988.

[16] J. A. Steppe, S. H. Oliveau, and O. J. Sovers, "Earth Rotation Parameters From DSN VLBI: 1991," JPL Geodesy and Geophysics Preprint no. 210, April, 1991 (submitted to the International Earth Rotation Service Annual Report for 1991).

Table 1. Late 1990s spacecraft–quasar differential VLBI error budget.

Error source	Magnitude, nsec
Quasar SNR	0.11
Spacecraft SNR	0.033
Quasar position	0.066
Clock offset	0.030
Clock instability	0.003
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 2. Clock rate estimates.

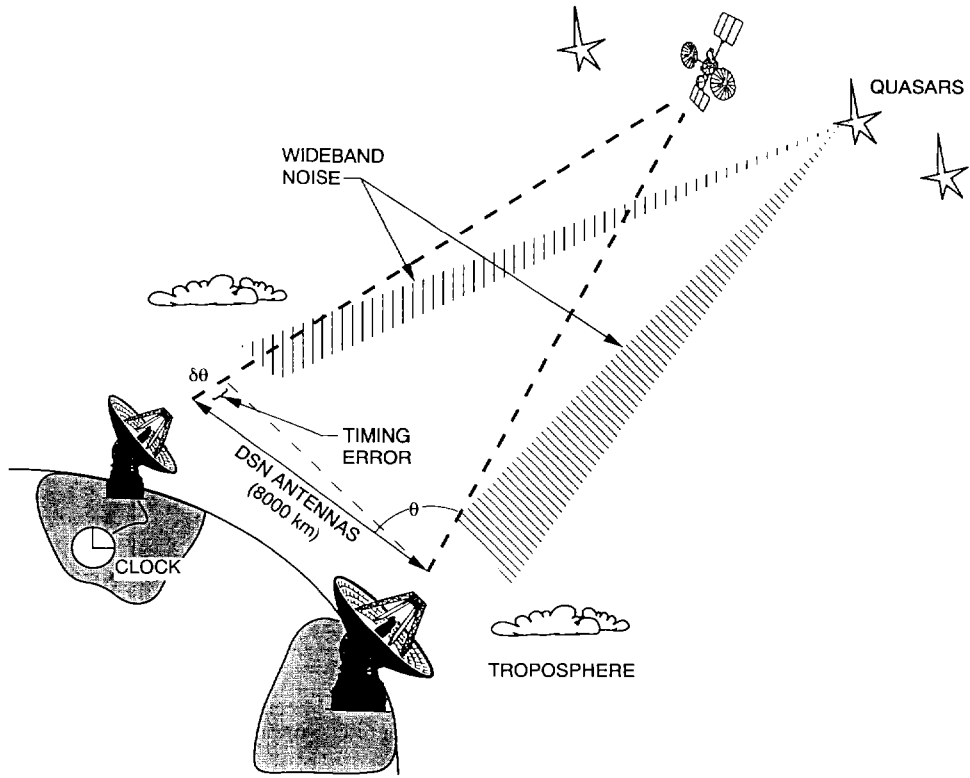| Date, 1991	Baseline	VLBI, nsec/day	GPS, nsec/day
January 23	Canberra–Goldstone	−10.0 ±1.6	−9.0 ±0.9
January 27	Madrid–Goldstone	−4.5 ±2.2	−2.7 ±0.5
January 30	Canberra–Goldstone	−7.9 ±3.1	−9.1 ±0.9
February 6	Canberra–Goldstone	46.6 ±1.3	46.4 ±1.9
February 10	Madrid–Goldstone	5.9 ±1.8	2.8 ±0.4

Fig. 1. Spacecraft tracking using quasar-differenced differential one-way range.
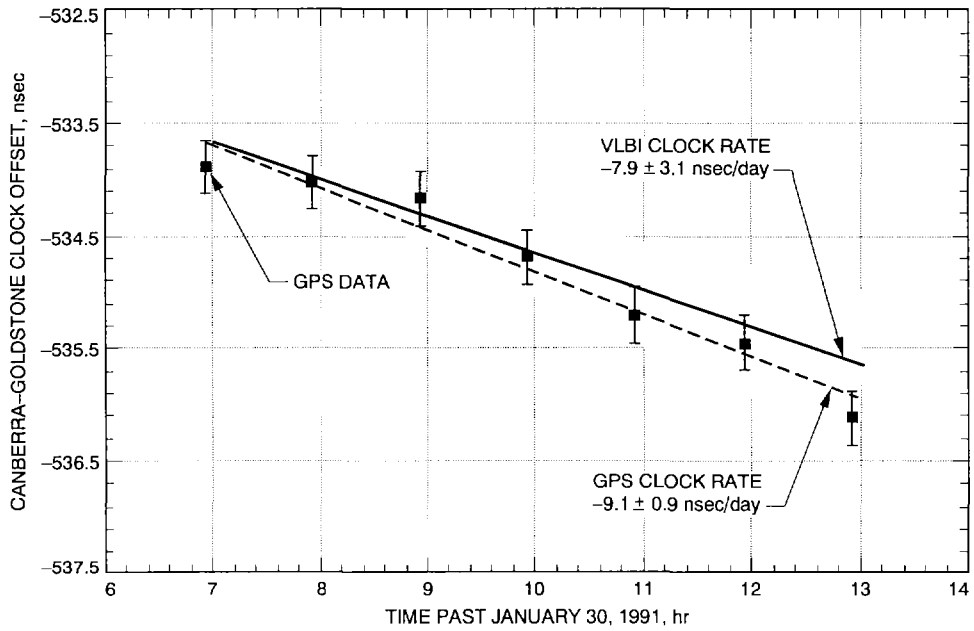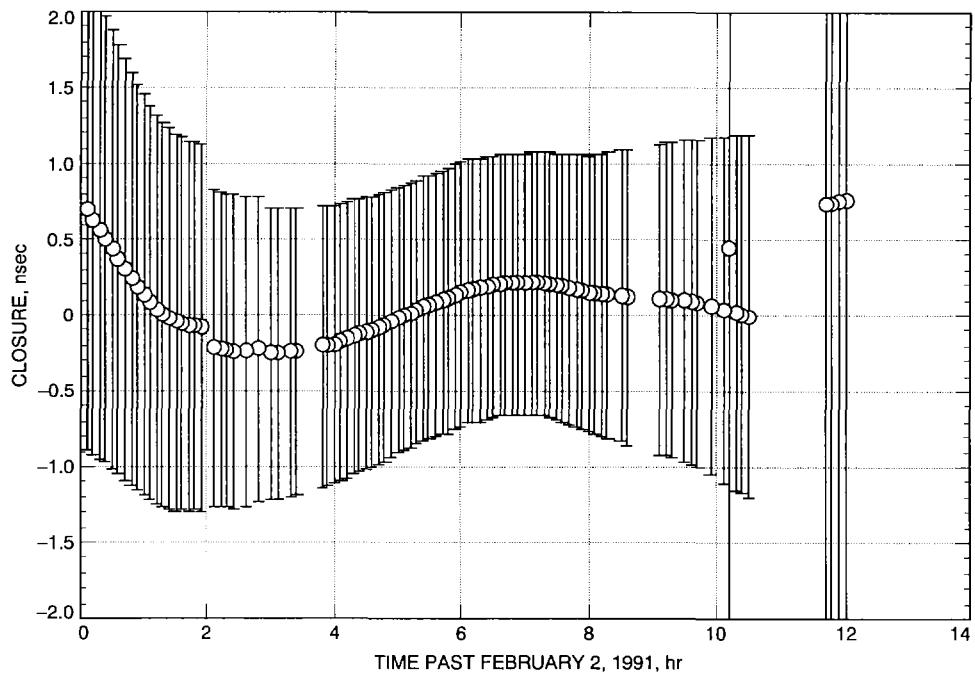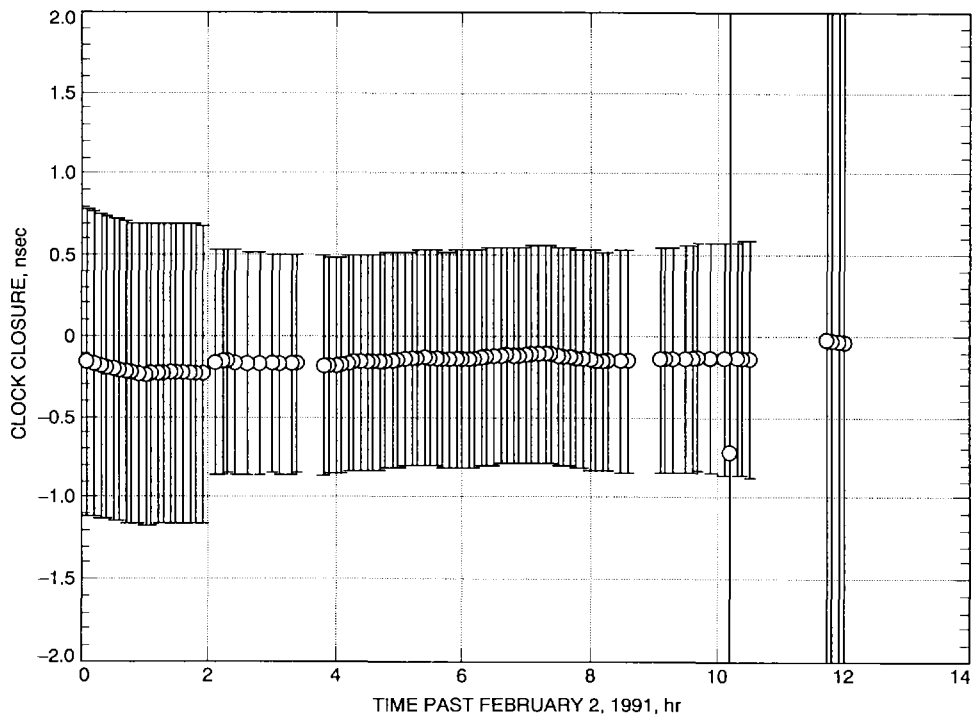

Fig. 2. GPS-based clock estimates and linear fit.

Fig. 3. Canberra–Goldstone–Madrid clock closure with unconstrained GPS satellite orbits.

Fig. 4. Clock closure with GPS satellite orbits initialized from previous day.