USING THE GLOBAL POSITIONING SYSTEM FOR EARTH ORBITER AND DEEP SPACE TRACKING

Stephen M. Lichten, Bruce J. Haines, Lawrence E. Young, Charles Dunn, Jeff Srinivasan, Dennis Sweeney, Sumita Nandi, and Don Spitzmesser

Jet Propulsion Laboratory, California Institute of Technology

Abstract

The Global Positioning System (GPS) can play a major role in supporting orbit and trajectory determination for spacecraft in a wide range of applications, including low-Earth, high-Earth, and even deep space (interplanetary) tracking. This paper summarizes recent results demonstrating these unique and far-ranging applications of GPS.

LOW-EARTH ORBITER TRACKING

GPS satellites (presently numbering 25) transmit carrier signals at 1.228 and 1.575 GHz (L-band) which are modulated by a pseudorandom noise code, the P-code (precision code), at 10.23 MHz. A second code, the C/A (coarse acquisition) code, is somewhat noisier than the P-code due to its lower frequency at 1.023 MHz and the lack of dual-band ionospheric correction. The GPS codes include a navigation message with GPS clock and orbit information which can be utilized for real-time point positioning. With the P-code, user positions can be determined in a point (geometric) positioning mode in near-real time to about 10 m. In normal operation, the Department of Defense turns on *selective availability* (SA) for most GPS satellites, introducing a clock dither and alterations to the broadcast ephemeris. Certain authorized users can be equipped with keys to correct for these effects, but other users see transmitter clock variations of the order of 30-50 m.

Civilian and scientific uses of GPS have led to a wide variety of applications in geodesy, surveying, navigation, and remote sensing, including a cm-level non-real time positioning capability for receivers on the surface of the Earth [1], and several-cm accuracy for low-Earth satellite orbit determination [2-3]. Such high-precision applications require a global GPS ground network of high quality dual-band receivers and simultaneous processing of data in estimation software which incorporates detailed physical and observation models. Most military and civilian GPS applications involve an upward-looking geometry where the users' receiving antennas are pointed away from the Earth towards the GPS satellites. Fig. 1 shows this with the low-Earth orbiter Topex/Poseidon and ground stations tracking GPS satellites.

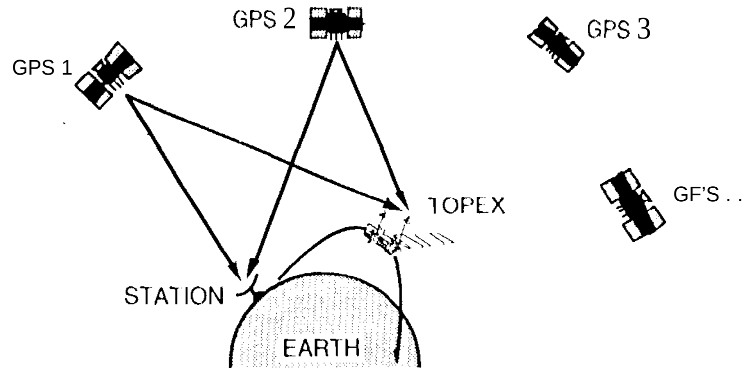


Fig. 1. Upwards looking geometry for low-Earth orbiter and ground stations tracking GPS satellites.

Topex/Poseidon carries an ocean altimeter to map the oceans' surfaces and measure global ocean circulation. At its altitude - slightly above 1300 km -- 6-8 GPS satellites are typically in view at a given time with the upwards looking hemispherical field of view. By relying at least partially on available precise dynamic models, a dynamical fit can be performed in a sequential filter using data over at least several hours and the accuracy of the solution improves significantly over that achieved from instant point solutions. Additional accuracy improvement results from differential cancellation of the receiver and transmitter clock errors (and SA clock dither) at each measurement epoch when the ground and flight receiver data are processed together. While this requires common visibility of at least two GPS with at least two receivers (Fig. 1), such geometry is continuously achieved at low altitudes with at least 6 ground sites. When all the GPS orbits are estimated as well, low-Earth orbit determination at the few cm-level is possible, as has been demonstrated on Topex/Poseidon [2-3]. Thus a low-Earth satellite, in the presence of SA, can be tracked to an accuracy ranging from 50-100 m (real-time geometric positioning), to a few tens of meters (real-time filtered GPS data), to 10 cm or better (differential GPS, ground network + modeling + filtering + smoothing). Radial accuracies achieved for Topex with GPS tracking are better than 3 cm **[2-3].**

HIGH-EARTH ORBITER TRACKING

Above 3000 km altitude, replacing the "upwards-looking" tracking configuration with a "down-looking" configuration results in more GPS satellites in view [4]. For the down-looking geometry, the orbiting user directs the receiving antenna down towards to Earth and tracks GPS satellites on the far side (GPS satellites broadcast a beam which is slightly wider than the angle which the Earth subtends.). Above 6000 km, more often than not, less that 4 GPS are in view, and above 10000 km, typically less than 2 GPS arc simultaneously tracked from the orbiter and even a differential solution is not always possible. This means that SA cannot always be removed differentially, and without SA keys, significant performance. degradation occurs [5].

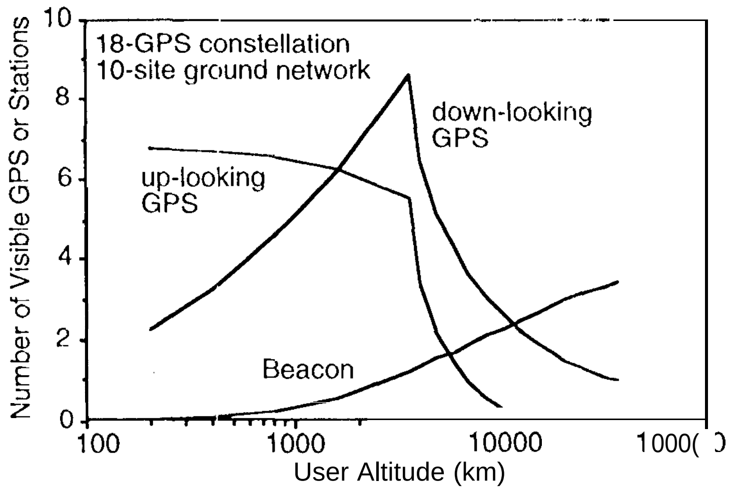


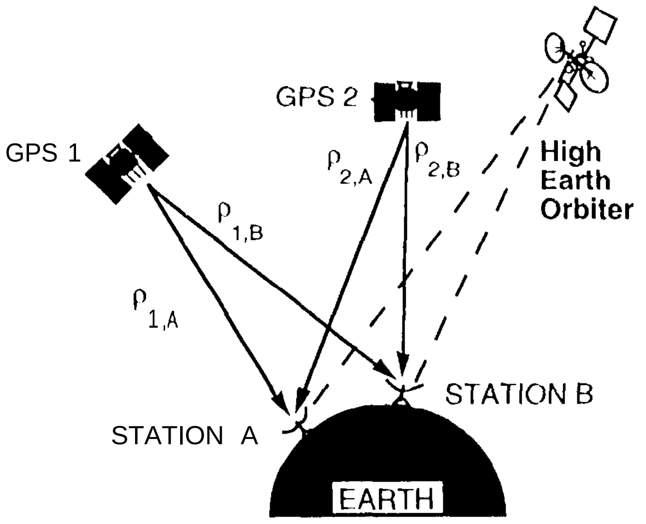
Fig. 2 Average number of GPS satellites in view for a satellite carrying a flight receiver (up-looking and down-looking GPS) and average number of ground stations in view as seen from a user satellite with a GPS-like beacon. The satellite equipped with a GPS-like beacon which can be tracked in a GPS ground receiver along with the GPS signals simultaneously.

Above 10000 km altitude, it becomes advantageous to consider a technique which we will refer to as GPS-like tracking (GLT) [6]. GLT incorporates a transmitting beacon instead of a GPS flight receiver on the user satellite, a beacon whose signal structure is such that it can be easily tracked in ground GPS receivers. Fig. 2 shows visibility curves for the upwards looking, downwards looking, and beacon (GLT) scenarios as a function of altitude. For the upwards and downwards looking configurations, the plot shows the average number of visible GPS satellites, while for the beacon, the plot shows average number of stations able to simultaneously track the high-Earth orbiter. 10 ground stations were assumed to be evenly distributed around the globe for this plot [4].

The downwards-looking technique (for the 2000-6000 km altitude range) has not yet been demonstrated in an actual flight test. This technique might require directional and steerable flight antennas. A magnified atmospheric distortion effect is also expected. The GPS signals will be weaker too, since they must travel a farther distance and the data would be sampled from the edge of the GPS broadcast beam pattern.

GPS-Like Tracking TDRS Experiment

in January 1994 the Jet Propulsion Laboratory (JPL) carried out a GLT experiment in which the Ku-band carrier phase data from two of NASA's geosynchronous TDRS (Tracking and Data Relay Satellite) orbiters were tracked in three TurboRogue receivers in the southwest United States which were specially adapted to track GPS satellites and TDRS simultaneously.



range
range (phase) bias
clock offsets

$$\Phi_{1,A} = [\rho_{1,A} + B_{1,A} + C_1 + C_A]\, 2\pi/\lambda$$
$$\Phi_{1,B} = [\rho_{1,B} + B_{1,B} + C_1 + C_B]\, 2\pi/\lambda$$
$$\Phi_{2,A} = [\rho_{2,A} + B_{2,A} + C_2 + C_A]\, 2\pi/\lambda$$
$$\Phi_{2,B} = [\rho_{2,B} + B_{2,B} + C_2 + C_B]\, 2\pi/\lambda$$

$$(\Phi_{1,B} - \Phi_{1,A}) - (\Phi_{2,B} - \Phi_{2,A})$$
$$= [(\rho_{1,B} - \rho_{1,A}) - (\rho_{2,B} - \rho_{2,A}) + B]\, 2\pi/\lambda$$

Fig. 3 Differential GPS-like tracking. Four simultaneous measurements of carrier phase (Φ) enable removal of transmitter and receiver clock offsets. After tracking for 12-24 hrs, the resultant linear combination of ranges enables estimation of GPS orbits to the level of a few tens of cm, and of ground coordinates to cm-level accuracy. The term B, in the final equation, is a composite bias term which is easily estimated from ~3 hrs of tracking. In GPS-like tracking (GLT), the carrier phase from the high-Earth orbiter would also be included and its orbit similarly estimated.

Fig. 3 shows schematically how GLT relates to differential GPS tracking (discussed at length in [6-7]). in principle, this could be a powerful technique for orbit determination, since GPS orbits are routinely determined at JPL (and several other analysis centers) to better than 50 cm, and the accuracy of the high-Earth satellite's orbit could, under ideal circumstances, approach that of the GPS satellites. Fig. 4 shows how overlapping data arcs of 30 hrs are used to assess the quality of orbits produced at the Jet Propulsion Laboratory. During a recent 1-week period in December 1993, for 25 GPS satellites the ave.rage rms overlap difference was 37 cm (RSS three-dimensional). During that week, the lowest rms was for PRN 22 (8 cm) while the highest rms was for PRN13 (109 cm).

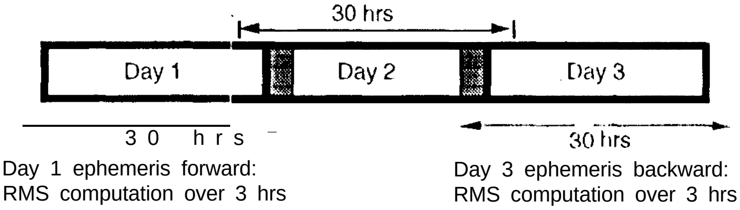


Fig. 4 Assessment of GPS orbit quality from daily GPS precise orbit determination at the Jet Propulsion laboratory.

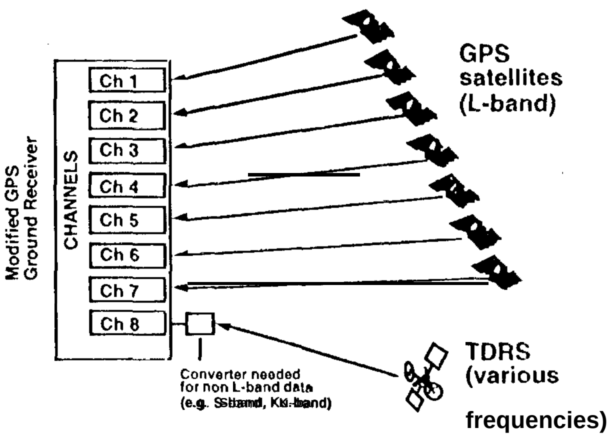


Fig. 5 Schematic for modified GPS ground receiver to simultaneously track a high-Earth orbiter along with GPS satellites. In the TDRS experiment, a small separate antenna with a downconverter was added to the GPS ground instrument to mix the Ku-band TDRS carrier phase down to L-band before the TDRS data were added to the other GPS L-band data.

GPS-compatible beacon signals could include: (1) an actual GPS L-band beacon; (2) a set of tones which can be tracked in a GPS ground receiver; and (3) the carrier phase from telemetry, tracked in a GPS receiver. Use of an actual GPS beacon (case 1) will not be discussed in this paper, but it has been considered for other geosynchronous satellites [8]. A suitably designed beacon (case 2), however, could transmit a set of tones at I.-band which could be tracked in the GPS receiver with minor modifications. A GPS receiver which ordinarily tracks 8 GPS satellites could be adapted to track 7 GPS satellites -i tones from one other satellite. With an adequate bandwidth separating the tones, ambiguities could be resolved and a cm-level quality range measurement could be possible, Case 2 would in general require placing a new beacon on the user satellite, but preliminary designs for such beacons being studied at JPL show that a beacon made from commercially available parts is feasible and could be relatively inexpensive in terms of cost, mass, and power, at least when compared to GPS flight receiver payloads. The third approach, tracking carrier phase from the user satellite, would be subject to any limitations on the availability of the current carrier signals from the spacecraft, For either case 2 or 3, the beacon need not be at the GPS L-band frequency; a simple downconversion to L-band would be used prior to feeding the non-GPS signal to the GPS ground receiver (Fig. 5). This was, in fact, done at JPL for the TDRS GPS tracking demo.

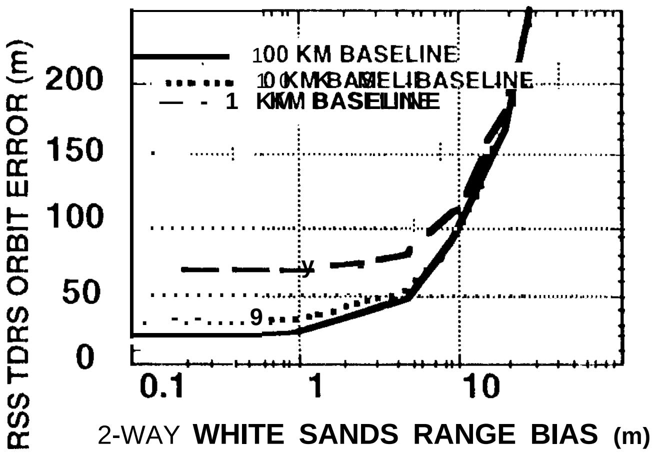


Fig. 6 Expected TDRS GPS demo orbit determination accuracy is shown in lower portion. Actual baselines in the demo arc 300-1000 km.

The TDRS tracking experiment utilized three ground terminals, each of which included a GPS TurboRogue receiver. These GPS receivers were modified at JPL to track 7 GPS (carrier phase and pseudorange) satellites + 1 TDRS (Ku-band carrier phase) simultaneously (Fig. 5). Initially it was planned to deploy the three ground terminals within approximately 100 km of White Sands, New Mexico. The small network size is necessitated by the small TDRS footprint at White Sands, and offers a number of operational advantages as well. Because TDRS satellites are geostationary, carrier phase by itself provides a very weak determination of the longitude orbit component. A small amount of two-way range data (regularly collected at White Sands) would be adequate to determine the longitude orbital component. Fig. 6 shows anticipated orbit determination accuracy as a function of two-way range precision. The eventual goal is to show that the system could meet a near-real time (within 2 hrs) 50-m operational orbit determination requirement. Other analysis at JPL has shown that if a geosynchronous satellite were equipped with a simple ranging (tones) beacon, the expected orbit accuracy from a global tracking network from GLT would be about 3 m [7]. in the case of TDRS, however, existing signal structure and the limited ground footprint put constraints on the performance, and it is expected that the TDRS orbit determination will be about a factor of ten less accurate than the ideal case, The actual ground network size for the experiment was 1000 km x 300 km, which should result in higher accuracy than for the case of 1 ()()x100 km. The 1000 km line resulted from deployment of one ground receiver at J]']. in California, where the first side.lobe of the TDRS ground footprint happened to be detectable.

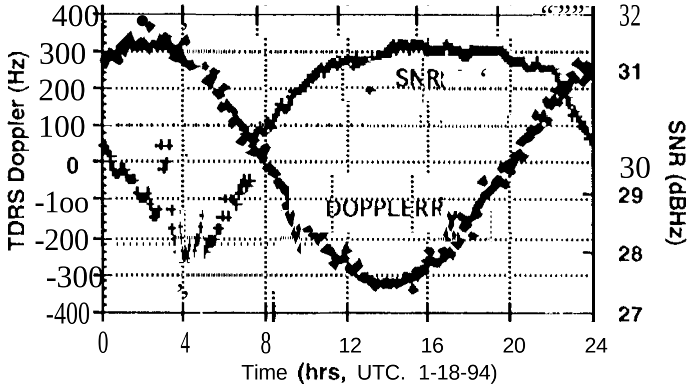


Fig. 7 TDRS carrier phase tracked at JPL with modified GPS receiver during the recent TDRS/GPS demonstration experiment.

Fig. 7 shows a sample of TDRS carrier phase (raw data) tracked in the JPL site GPS receiver during the January 1994 experiment. Detailed orbit results and a complete discussion of the TDRS/GPS tracking experiment will be presented in a future paper. The diurnal Doppler signature expected from a geosynchronous satellite orbit is clearly visible. The variations in SNR arc believed to be due to the fact that JPL is located in the first sidelobe of the transmit antenna pattern, and the strength of the received signal is sensitive to the small motion of the satellite relative (o J]'],.

Advantages of GPS-Like Tracking

The incorporation of GPS ground terminals into a ground tracking network for orbit determination of other satellites --- as in GLT — results in a very powerful tracking system. Previous analysis has shown that a global GPS/GLT tracking network could routinely provide orbit determination to the level of several meters for satellites at geosynchronous to 100000 km altitude. However for virtually any tracking configuration (including the more constrained TDRS one), collocation of ground tracking terminals with GPS receivers has significant advantages: precise (nanosec-level) time transfer between ground sites from GPS; ionospheric delay calibrations from dual-band GPS data; precise tropospheric delay calibrations from GPS; and the capability to accurately solve for the locations of the ground sites and for variations in Earth orientation from GPS global data, Significant error sources in the orbit determination of high-Earth satellites can thus be controlled, and the combined tracking system utilized in GLT provides a means to calibrate most of them to the few cm-level. JPL's GPS analysis is highly automated; incorporation of the high-Earth orbiter into such a data processing system offers a number of operational advantages.

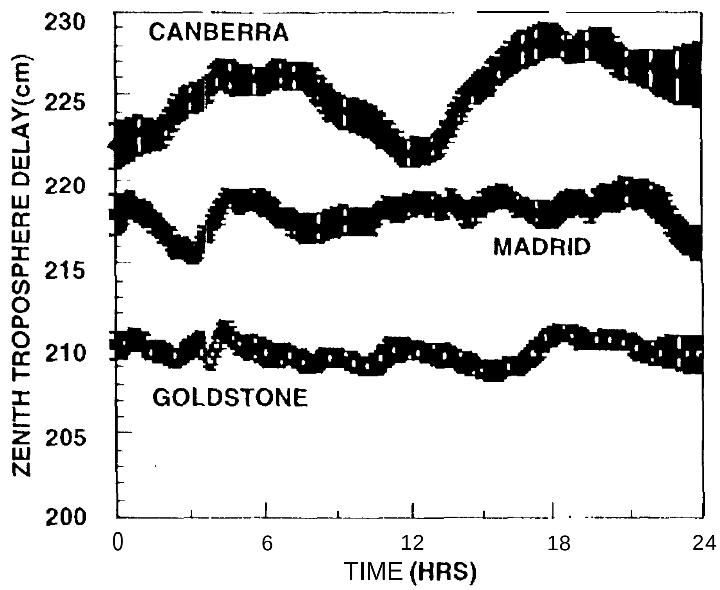


Fig. 8. Zenith troposphere delays at the 3 NASA DSN sites measured with GPS. Width of lines indicates precision of GPS estimates (+/-1σ), better than 1 cm most of the time.

APPLICATION TO DEEP SPACE TRACKING

In the TDRS/GPS demo, a small horn antenna (opening dimensions 17 x 14 cm) was used side by side with the usual GPS omni antenna, and the outputs of the two antennas were combined after downconversion of the 13.731 Ghz TDRS signals to GPS L-band. For deep space tracking, a very large ante.nna collection area (tens of meters) is often needed. Even when the ground GPS receiver is separate from the deep space tracking receiver, the two receivers can be collocated and synchronized to the same frequency standard (a hydrogen maser at the JPL deep space tracking sites) and thus exploit many advantages of GLT for deep space, Geodetic and atmospheric calibrations from GPS, in fact, assume even greater importance for deep space tracking. Fig,. **8** shows a sample of calibrations from a prototype GPS-based calibration system for troposphere path delays at the three DSN sites. When made operational, such a calibration system could eventually support a deep space navigation capability between 10 and 50 nanoradians angular accuracy, depending on the level of other systematic errors in the deep space data, Use of GPS for Earth orientation calibrations could potentially make available significant amounts of large antenna time currently needed for geodetic calibrations.

SUMMARY

The Global Positioning System (GPS) can support orbit determination and navigation over a wide altitude range of altitudes. At the lower altitudes, upwards looking GPS tracking can provide several-cm orbit accuracy. At higher altitudes, GPS-like tracking (GLT), incorporating a flight beacon which can be tracked in ground GPS receivers provides an accurate and efficient orbit determination technique. Flight demonstrations have been carried out for both of these approaches. For deep space applications, GPS ground receivers collocated with the deep space tracking antennas can provide essential geodetic and atmospheric data. A prototype deep space calibration system utilizing GPS at JPL has demonstrated the feasibility of this approach.

A cknowledgement: The work described in this paper was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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