

"Innovation" is a regular column in GPS World featuring discussions on recent advances in GPS technology and its applications as well as on the fundamentals of GPS positioning. This month we present an article on the use of GPS receivers on board orbiting spacecraft to determine their orbits with unprecedented accuracy. Our author is Thomas Yunck, Deputy Manager of the Tracking Systems and Applications Section of Caltech's Jet Propulsion Laboratory in Pasadena, California.

This column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Surveying Engineering at the University of New Brunswick. We appreciate receiving your comments as well as suggestions of topics for future columns.

The claim that we can track the position of a bulky earth satellite continuously with an accuracy of a few centimeters may seem about as plausible as the suggestion that it might be desirable to do so. But space-based altimetry for ocean circulation experiments requires that level of accuracy — and the Global Positioning System (GPS) may be the only practical way to achieve it.

New orbit estimation techniques made possible by GPS differ in fundamental ways from those in use since Sputnik. And although the GPS system design dates to the mid-1970s, we have only recently recognized the potential of these techniques. This is just one of the startling bonuses that have turned GPS into something of a windfall for earth science.

The essential difference GPS offers is comprehensive coverage. Never before has it

A New Chapter in Precise Orbit Determination

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been possible to track an earth satellite in three dimensions without interruption. But by placing a GPS receiver aboard the satellite, we can observe its true motion and reconstruct its trajectory in great detail without knowledge of the forces acting on it. Consequently, orbit accuracy need not be degraded by unpredictable satellite dynamics. Only the accuracy of the GPS carrier-phase observable, which can be better than 1 centimeter for a 1-second duration observation, ultimately limits "user orbit" accuracy.

ORBIT ACCURACY

In recent years, the needs of space-based altimetry for the study of global ocean circulation have stimulated advances in low-altitude precise orbit determination. Examples of recent ocean altimetric satellites include Seasat (1978); Geosat (1985–1990); ERS-1, the first European Remote Sensing satellite, launched in 1991; and the U.S.–French TOPEX/Poseidon satellite, launched this past August.

Figure 1 illustrates a central problem in the study of ocean circulation by altimetry. Of interest are the systematic departures of the sea surface from the geoid — the surface of constant gravitational potential at sea level — caused by the forces that drive ocean circulation. This sea surface topography (with a permanent component reflecting steady-state global circulation and a variable component reflecting temporal circulation changes) is exquisitely subtle, with a peak amplitude of about 1 meter (at the Gulf Stream), its minute swells stretching across hundreds of kilometers. The best satellite altimeters measure height with about 2-centimeter precision over a footprint of several kilometers. But the host satellite's altitude can vary by hundreds of meters around an orbit, confounding the surface signal. To extract the most information

from precise altimetry, we must continuously track the satellite's geocentric altitude to the same level of accuracy achieved by the altimetry measurements.

The TOPEX/Poseidon science team has set a formal mission requirement of 13 centimeters for the root-mean-square (rms) altitude error — roughly three times better than has been achieved for Seasat, but well above the 2.4-centimeter precision of its altimeter. Because orbit error is a limiting factor in ocean altimetry and altimeter precision will continue to improve, an international panel of oceanographers recently recommended the pursuit of technology developments that lead to orbits of altimetric satellites with no more than 1 centimeter rms error.

DYNAMIC ORBIT DETERMINATION

Conventional ground-based tracking systems (one-way range rate or Doppler for Seasat, Geosat, and ERS-1; laser ranging for TOPEX/Poseidon) seldom provide coverage from more than one direction at a time and often have periods of no coverage. To supply the missing information, investigators must fit an orbit model to the tracking data. The most precise orbit estimation strategies are derived from models of the forces acting on the satellite, a technique known as dynamic orbit determination.

The technique begins with a set of tracking measurements (range or Doppler, for example), models of the forces, and the satellite mass. These models yield a model of satellite acceleration over time from which, by double integration, we can form a nominal or a priori trajectory. To produce the orbit solution we need only determine the two vector constants of integration — the initial position and velocity — also known as the epoch state. A least-squares estimation procedure finds the epoch state for which the resulting model trajectory best fits the tracking data. To improve the fit, we can adjust various model parameters, such as those describing atmospheric drag and solar radiation pressure or gravity field coefficients. The resulting solution, however, is still a *model* trajectory, and its accuracy depends on how faithfully the force models, fixed or adjusted, describe the real forces acting on a satellite. When our goal is centimeters over fitted orbit arcs of many days, those models must be surpassingly fine.

As a practical matter, centimeter-level dynamic modeling may long be out of reach for complex vehicles at altitudes below 1,000 kilometers, where gravity model errors and variable drag effects become prominent. The best solutions for Seasat and Geosat, both orbiting at a height of about 800 kilometers,

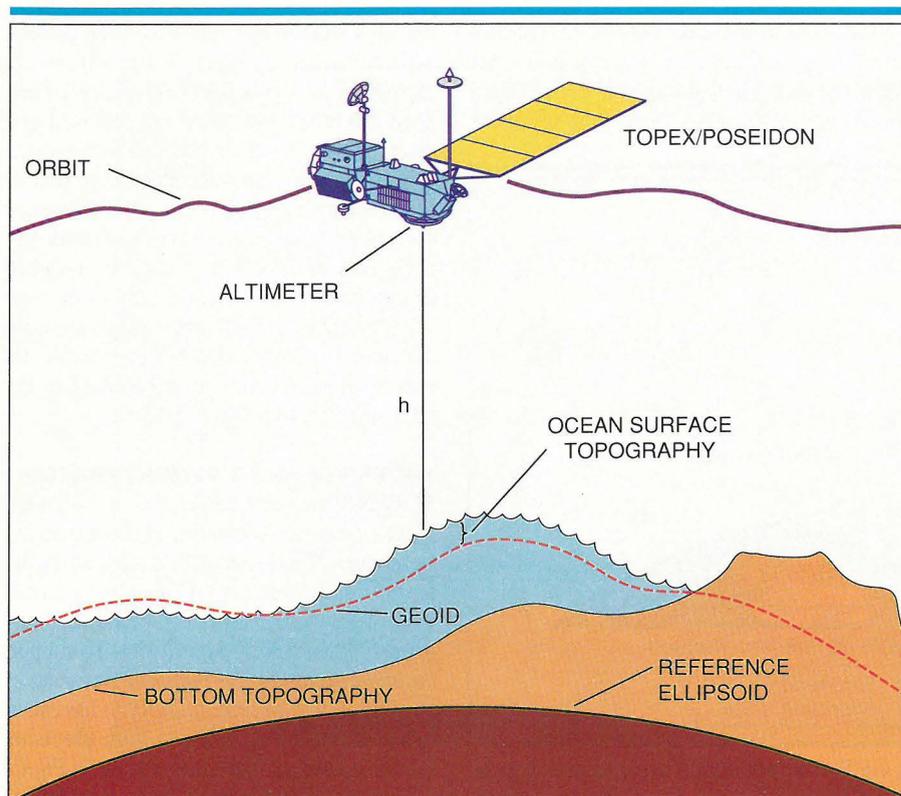


Figure 1. A major challenge in interpreting precise ocean altimetry data is the removal of satellite altitude variations, thereby exposing sea surface topography with a precision comparable to that of the altimeter measurements.

are accurate radially to 25–40 centimeters. Scientists chose TOPEX/Poseidon's relatively high altitude of 1,336 kilometers primarily to reduce dynamic model error.

KINEMATIC TRACKING WITH GPS

Continuous three-dimensional tracking with GPS allows us to discard detailed force models in a purely kinematic orbit solution, illustrated in Figure 2. (The study of kinematics deals with motion without regard to the forces causing it.) Deficiencies in the force models yield distinct post-fit residuals — discrepancies between the actual measurements and theoretically predicted measurements based on the dynamic solution.

With sparse conventional tracking data, postfit residuals are useful to indicate the quality of the orbit fit and perhaps to suggest ways in which the solution might be improved, but they offer little immediate benefit. By contrast, continuous data from multiple GPS satellites enable us to construct at every time point a full three-dimensional residual vector between the dynamic solution and the measurements. In short, we can assemble the complete observed trajectory geometrically from a dynamic solution and its postfit residuals.

In practice, we can build the kinematic solution from a dynamic solution by solving for a local three-dimensional force correction at each time step. Each correction represents the incremental force needed to explain the observed departure from the model orbit over the last time step. In the pure kinematic solution, we estimate the force correction independently at each step without constraint. This is equivalent to modeling the residual path as a white noise process with large variance. (White noise results from a random or stochastic process in which all values are mutually uncorrelated and all frequencies are represented equally.) The resulting position solution depends solely on the measurements, and dynamic model errors vanish.

In general, simple combination of the dynamic solution and GPS data is not optimal because the correlation between the corrections coming from the GPS data is not taken into account; that is, the white noise approach is sometimes a bit too simplistic. If we employ accurate force models in the dynamic solution, the residuals will be small, and we can benefit by placing constraints on the corrections, consistent with the force model errors. Moreover, if the model errors fail to decorrelate between time points, we

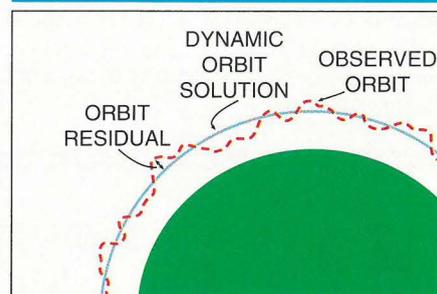


Figure 2. The kinematic tracking technique works by reconstructing the observed orbit from a dynamic orbit solution and the continuous three-dimensional measurement of residuals produced by that solution. The dashed line represents the true trajectory of a low orbiter subject to variable forces; the smooth line represents a simple dynamic orbit solution.

can benefit further by representing that correlation in the stochastic adjustment.

More generally, then, we can model the force corrections as colored (correlated) noise with a variance that reflects actual force model errors. This reintroduces some dependence on force models and hence some sensitivity to model errors. But if we choose the variance and correlation model carefully, we can exploit the useful dynamic information and minimize dynamic error. This *reduced dynamic solution* offers several advantages over the pure kinematic form (which is a special case), including lower sensitivity to varying observing geometry and a solution that is closer to the actual orbit. Both approaches can effectively remove another altimetric bugaboo: geographically correlated orbit error, or error that is consistently greater over certain regions (often the oceans) where conventional tracking is sparse.

For dynamically complex vehicles, even the best force models may add little to the orbit solution, and the optimal weighting will be effectively kinematic. In that case we can simplify the solution by discarding force models and adopting the kinematic form. If care is taken to ensure strong observing geometry, the kinematic solution can be very robust.

THE WHOLE PICTURE

Those familiar with GPS know that when a position is determined solely from GPS data, GPS ephemeris and clock errors can enter at a level of several meters or more. We can reduce this problem for an orbiter by adopting a global form of differential GPS positioning, illustrated in Figure 3. A global

network of ground-based receivers, some at points with positions known to 1-2 centimeter accuracy, continuously tracks all GPS satellites in view.

GPS data from the orbiter and ground sites are then combined in a grand solution for GPS and user orbits, some or all ground positions, and such other quantities as phase

biases, receiver and satellite clock offsets, and atmospheric delays. All positions are recovered in a consistent reference frame, and GPS orbits and clocks are removed as a direct source of error. The GPS broadcast ephemeris is discarded, and the effects of selective availability (navigation message corruption and dithering) are removed. For orbit arcs of less than a day, the reduced dynamic solution is applied only to the user orbit, whereas the GPS orbit solutions remain dynamic. For longer arcs, however, weak stochastic adjustments may be applied to the GPS satellites as well.

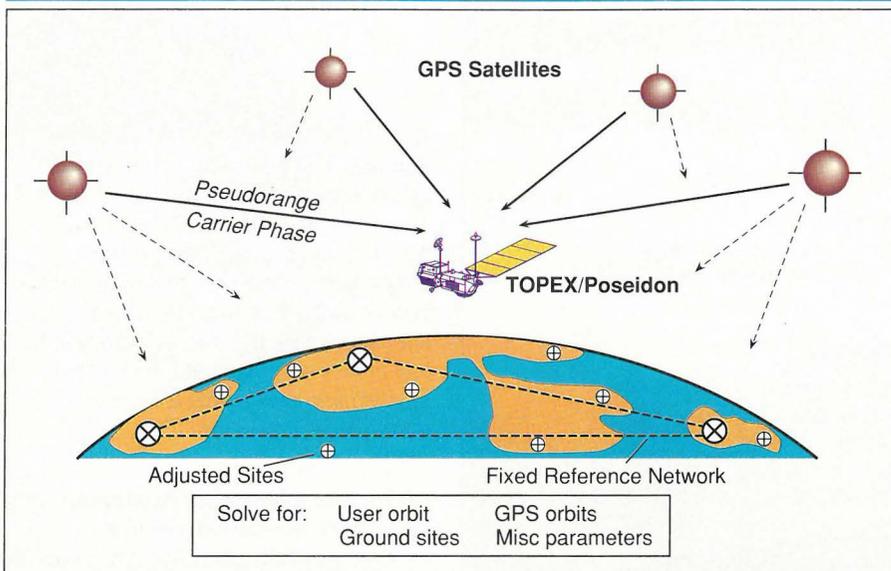


Figure 3. Global differential tracking removes GPS orbit and clock error to reach sub-decimeter orbit accuracy.

TOPEX/POSEIDON DEMONSTRATION

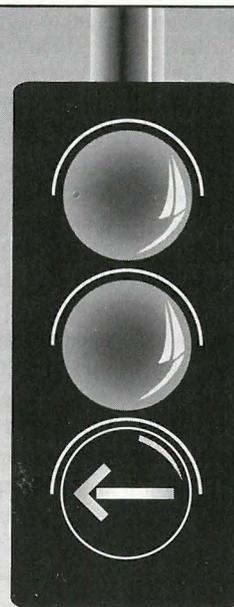
TOPEX/Poseidon carries a six-channel P-code receiver to demonstrate these tracking techniques. The investigating team at the Jet Propulsion Laboratory (JPL) has set a formal goal of 10-centimeter rms altitude accuracy for the GPS tracking experiment. To support the demonstration, the National Aeronautics and Space Administration (NASA) has established a six-site network of high-precision P-code receivers. The sites, shown in Figure 4, include NASA's three Deep Space Net-

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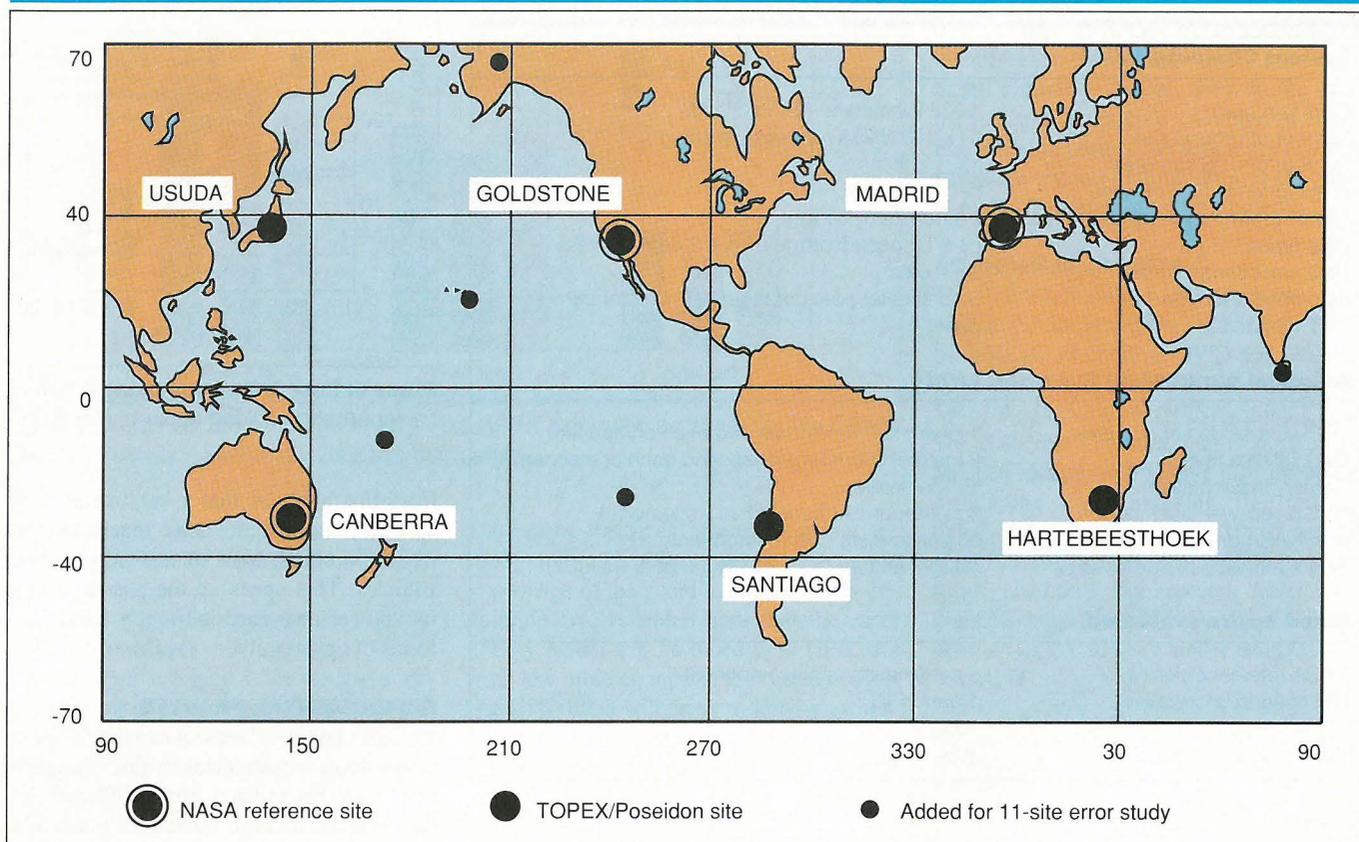


Figure 4. Six ground tracking sites will support the TOPEX/Poseidon GPS tracking experiment.

work tracking complexes in California, Spain, and Australia, and complementary sites in Japan (receiver owned and operated by the Institute for Space and Astronautical Studies), South Africa (receiver owned and operated by Centre National d'Etudes Spatiales, the French space agency), and Chile (receiver installed by NASA and operated by the University of Chile in Santiago). The five additional sites were used for a theoretical

study of enhanced GPS tracking for the Space Shuttle.

JPL investigators have conducted extensive error studies for the TOPEX/Poseidon GPS experiment. One technique, covariance analysis, maps a set of assumed measurement and modeling errors through the solution process to reveal their effect on the quantities estimated. Figure 5 shows the estimated rms altitude error as a function of the quality of the available gravity field model for three strategies: dynamic, kinematic, and optimal reduced dynamic. The full horizontal scale of Figure 5 represents roughly the accuracy of the GEM-T1 gravity model produced by the Goddard Space Flight Center in the mid-1980s. In very approximate terms, this model can depict differences in the strength of gravity of a bit less than one part in 10^5 over a distance of 1,000 kilometers. Arrows indicate the approximate gravity model error at launch (GEM-T3) and the expected quality after the gravity model is "tuned" (adjusted) with the flight data. Table 1 shows key assumptions used in the analysis.

dynamic strategy surpasses both. In principle, if our dynamic models are perfect, the optimal and dynamic strategies will converge because we would derive no benefit in deweighting dynamics with a geometric correction. Here, as the gravity model approaches perfection, the optimal solution retains a small advantage because errors in solar radiation pressure and atmospheric drag models remain. Of course, any computer analysis is idealized to some degree, and other small effects unaccounted for here are likely to emerge. A 5-centimeter altitude error is a reasonable expectation for the TOPEX/Poseidon experiment.

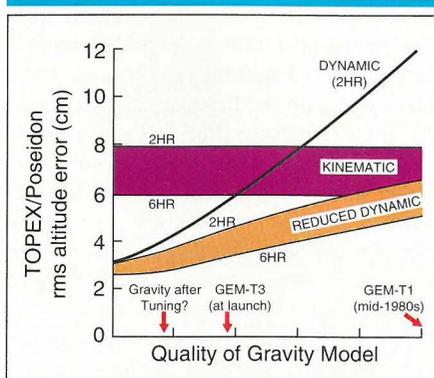


Figure 5. Error analysis comparing dynamic, kinematic, and reduced dynamic strategies for TOPEX/Poseidon mission.

FUTURE MISSIONS

At a lofty 1,336 kilometers, TOPEX/Poseidon presents a relatively modest test, even for a dynamic solution. Future challenges will include bulkier vehicles at lower altitudes: the Earth Observing System (EOS) at 700 kilometers, the Space Station at 400 kilometers, and the Shuttle as low as 300 kilometers — vehicles for which model errors will be meters to hundreds of meters and that are ordinarily considered inhospitable to ocean altimetry. The Shuttle presents the most severe modeling difficulties but is also

Table 1. Assumptions for TOPEX/Poseidon error analysis

System Characteristics	
Orbit (circular)	1,336 kilometers, 66° inclination
Number of ground sites	6 (with 3 NASA reference sites)
Number of GPS satellites	18
Flight antenna field of view	hemispherical
Flight receiver tracking capacity	8 satellites (L1 & L2)
Data types	L1 & L2 pseudorange/L1 & L2 carrier phase
Data smoothing interval	5 minutes
Smoothed data noise	5-centimeter pseudorange/5-centimeter carrier phase
Adjusted parameters & a priori errors	
TOPEX/Poseidon epoch state	1 kilometer; 1 meter/second each component
GPS satellite states	2 meters; 0.2 millimeter/second each component
Carrier-phase biases	10 kilometers
GPS & receiver clock biases	3 milliseconds (modeled as white noise)
Non-NASA ground locations	10 centimeters each component
Zenith atmospheric delay error	10 centimeters (modeled as random walk)
Fixed errors evaluated	
NASA reference positions	5 centimeters each component
GM of earth uncertainty	1 part in 10 ⁸
Atmospheric drag	10%
Solar radiation pressure	10%

uniquely attractive as a host because it allows for short-term trials of "reflyable" instruments.

For more robust tracking, let us enlarge the assumed GPS constellation to the full 24 satellites and reduce the nominal reference site error from 5 to 3 centimeters. Figure 6 shows the predicted kinematic orbit error for EOS at 700 kilometers, as a function of data arc length. The figure shows results for four data combinations: carrier phase only, carrier plus pseudorange (two levels), and a fictitious carrier-quality pseudorange that establishes a performance bound. In each case, data combinations are assumed for all ground sites as well as the flight receiver.

Figure 6 suggests that biased carrier phase by itself can approach the ideal performance of the fictitious carrier-quality pseudorange. It may seem surprising that the kinematic solution works at all with carrier phase alone. The grand solution, after all, must estimate phase and clock biases, and absolute pseudorange helps constrain those biases. The dynamic core of the kinematic solution allows the biases to be recovered sufficiently well with just carrier phase, although it takes more time to approach the common error floor set by phase noise and geometry. It should be noted that we made no attempt to fix cycle ambiguities; we adjusted phase biases as continuous variables.

The carrier-only solution is more than just a curiosity. From a practical standpoint, it allows extremely accurate tracking with simple codeless receivers, bypassing the effects of anti-spoofing. In another variation it can achieve fair orbit accuracy with single-frequency C/A-code data. Thus far we've assumed dual-frequency elimination of ionospheric delay; but we can also remove the ionosphere by averaging L1 phase and pseudorange to cancel the equal but opposite ionospheric effect on each. The resulting observable has the form of biased carrier phase with a noise level half that of pseudorange. We can then smooth the noise over periods of minutes (dynamically or with a polynomial) and use the result in the kinematic or reduced dynamic solution. Expected position accuracy in an L1-only kinematic differential solution for the Shuttle at 300 kilometers is better than 50 centimeters.

To test the limits of purely kinematic tracking, let us now assume a full-sky field of view (the Shuttles are equipped with GPS antennas top and bottom to allow this), an all-in-view flight receiver, and an 11-site ground network with 1.5-centimeter reference site error (see Figure 4). Figure 7 shows the predicted error in all position components for a demanding 300-kilometer Shuttle orbit for three arc lengths. The limiting error now approaches 1 centimeter. We may conclude

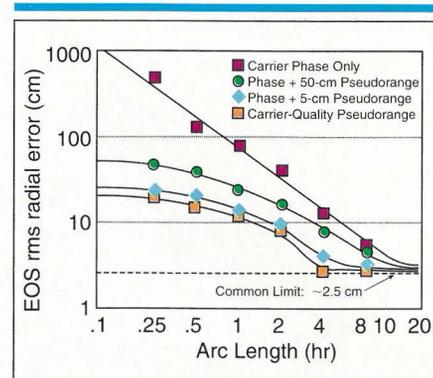


Figure 6. Error analysis showing potential kinematic tracking accuracy for EOS.

from this analysis that 1-centimeter orbit accuracy may be not only reachable, but reachable on the most dynamically suspect vehicles. This opens up the possibility for low-power near-earth altimetry from platforms of opportunity.

EXPERIMENTAL RESULTS

In light of these claims, it is worthwhile to review some experimental results. Though no results are yet in hand from TOPEX/Poseidon, researchers have carried out much relevant ground-based work.

The International GPS Geodynamics Service organized a geodetic campaign employing dozens of receivers worldwide in the summer of 1992. In one study, investigators rotated a four-day JPL solution for 28 GPS receiver positions into alignment with the existing International Terrestrial Reference Frame (ITRF). The ITRF comprises more than 100 sites around the globe whose coordinates have been determined by very long baseline interferometry and satellite laser ranging over many years. The global rms discrepancy between the 21 sites in common with the ITRF was 1.5 centimeters over all components. Daily baseline solutions from this campaign repeat in length to about 3 parts in 10⁹ (3 millimeters for each 1,000 kilometers) up to distances of more than 10,000 kilometers. Dual-frequency phase residuals are typically 3-4 millimeters. In an earlier global experiment, when a fixed station was adjusted kinematically every 6 minutes, the rms departure over 24 hours from the standard long-arc solution was less than 3 centimeters.

Although such results cannot confirm expectations for TOPEX/Poseidon, they suggest that the techniques for centimeter positioning with GPS are in hand and that the major error sources are understood. Because kinematic tracking introduces no new

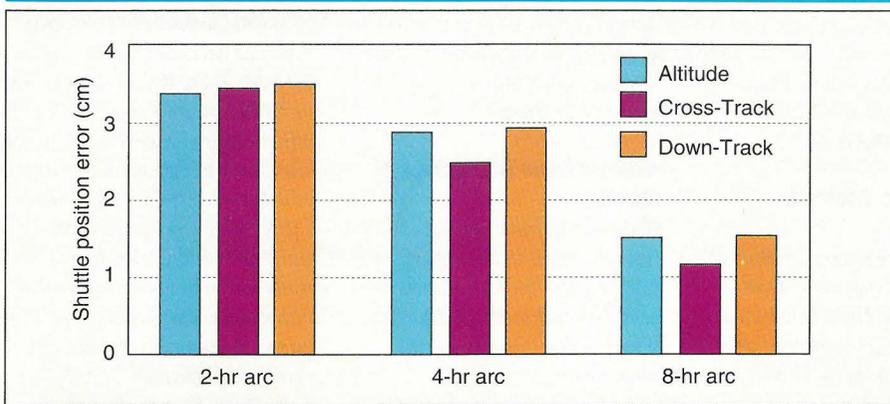


Figure 7. Improved observing geometry could push kinematic accuracy for the Space Shuttle to nearly 1 centimeter in all components.

sources of error (such as dynamic mismodeling), its extension to earth satellites should present few surprises.

FINAL COMMENT

Turning again to Figure 1, we see that a second element confounds ocean altimetry: the geoid. Undulations of the geoid (with respect to a best-fitting ellipsoid) are on the order of

100 meters, 100 times those of the sea surface topography. Therefore, we need accurate knowledge of the geoid to expose ocean circulation. We've noted here that the earth gravity model can be tuned with GPS data from low orbiters; indeed, the blanket coverage GPS offers will bring to gravity estimation the same strengths it brings to orbit determination. Researchers have derived

many current gravity models from satellite tracking data with gaps in coverage — frequently over the oceans where, for ocean-based altimetry studies, they do the most harm. Continuous GPS coverage of future missions will correct this deficiency and help attack the second limiting error in the study of ocean circulation through altimetry.

ACKNOWLEDGMENTS

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