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TOWARD DECIMETER TOPEX ORBIT DETERMINATION USING GPS

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Several practical aspects of precision GPS-based Topex orbit determination are investigated. Multipath signals contaminating Topex pseudorange data are greatly reduced by placing the GPS antenna on a conducting backplate consisting of concentric choke rings to attenuate signals coming in from the Topex horizon and below, and by elevating it on a boom to keep it well above all reflecting surfaces. A proper GPS antenna cutoff view angle is chosen so that a sufficient number of GPS satellites with good geometry are in view while reception of reflected signals is minimized. The geometrical strength of the tracking data is optimized by properly selecting GPS satellites to be observed so as to provide data with moderate continuity, low PDOP, and common visibility with ground tracking sites. The tracking performance is greatly enhanced when three complementary sites are added to the minimum ground tracking network consisting of the three NASA DSN sites.

INTRODUCTION

The US/French Ocean Topography Experiment satellite known as Topex/ Poseidon (Ref. 1) will be launched in mid 1992. For its primary scientific mission, it will carry a microwave altimeter that will precisely measure ocean topography. To fully exploit the few-centimeter accuracy of the altimetry measurements, the radial component of the satellite orbit will have to be independently determined to the same level of accuracy. A nominal goal of 13 cm has been set, but Topex would benefit from an altitude accuracy well below a decimeter. Although the baseline tracking system will be ground-based laser ranging, an experimental GPS receiver will also be

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carried onboard to demonstrate the potential of recently proposed precise GPS tracking techniques.

Differential GPS techniques have been demonstrated to be capable of producing precise relative positioning for ground sites (Refs. 2–4). An accuracy of a few centimeters for baselines over continental distances has been reported (Refs. 3,4). The techniques can be extended to the orbit determination of low earth satellite, provided that the satellite is equipped with a high performance GPS receiver. Extensive analysis has been carried out at JPL for precise Topex orbit determination using differential GPS (Refs. 2, 5, 6). The analysis shows that various forms of differential GPS are capable of meeting the 13 cm Topex accuracy goal. Of these, the most promising form makes use of the reduced-dynamic tracking technique (Refs. 5,6). With this technique, the satellite dynamics are partly inferred from the precise GPS carrier phase measurements so that the dependence on an accurate dynamic model is reduced, thus lowering the damaging effects of mismodeling the dynamics such as the earth's gravity. The published analysis assumed idealized data acquisition conditions. In this paper, some practical aspects are investigated. These include the onboard GPS satellite selection algorithm, minimum GPS antenna view angle, ground tracking network configuration, and means to reduce multipath effects.

BACKGROUND AND ASSUMPTIONS

GPS-based precision orbit determination for Topex is based on a technique called differential GPS. Each GPS satellite transmits a signal at two L-band frequencies (1227.6 and 1575.42 MHz) with a P-code square-wave modulation (Ref. 7). Two data types can be derived from the GPS signal acquired with a properly designed receiver, the P-code pseudorange and carrier phase. For the Topex GPS demonstration, Topex and a network of uniformly distributed ground receivers will be equipped with high performance GPS receivers capable of making simultaneous precise pseudorange and carrier phase measurements to multiple GPS satellites. The ground network will include tracking sites at NASA's three Deep Space Network (DSN) stations and several complementary sites. Fig. 1 shows the hypothetical 6-site network and the ground track of the Topex orbit that have been used in error analyses in the past.

Two major error sources contaminating the GPS pseudorange and carrier phase measurements are the ionospheric delays and the transmitter and receiver clock errors. These two error sources can be eliminated by proper combination of the GPS pseudorange and carrier phase measurements. The two data types are combined in two steps. First, measurements at two L-band frequencies are linearly combined to remove the ionospheric delay effects; then the combined measurements from different receivers observing different GPS satellites are doubly differenced to eliminate any GPS and receiver clock (and instrumental) errors. Double differencing also helps to reduce GPS ephemeris error. The double differencing operation can be carried out explicitly in a pre-processing stage or, more efficiently, in the filter by solving for clock biases as white-noise processes (Refs. 2–6). The Topex GPS demonstration will adopt the reduced-dynamic technique, in which both pseudorange and carrier phase measurements are used in the filtering process. A 3-D force on Topex, treated as process noise, is estimated together with other parameters to desensitize the orbit

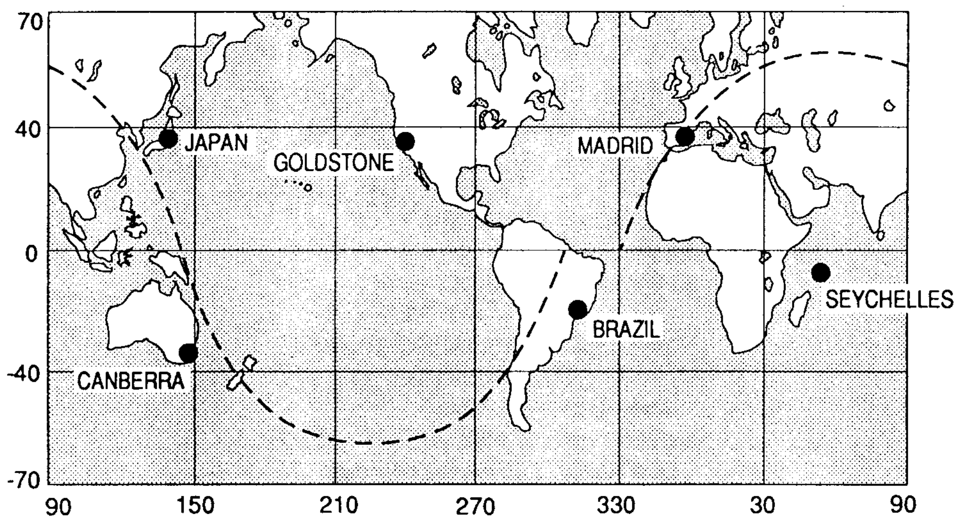


Fig. 1. A hypothetical ground tracking network and a Topex ground track

solution to the dynamic model errors. The degree of desensitization is determined by the parameters characterizing the process-noise force. These are the a priori uncertainty σ_0, the steady-state uncertainty σ_p, and the correlation time τ. In the following analysis, the reduced-dynamic technique with proper values for these parameters will be used for a near-optimum Topex orbit solution.

The ground tracking network and the nominal orbits of Fig. 1 will be adopted in the current analysis. Table 1 includes the error model and other assumptions used, unless otherwise stated. Here, we assume a constellation of 18 GPS satellites uniformly placed in six orbit planes. The Topex receiver is capable of simultaneously observing six GPS satellites while the ground receivers are capable of observing all visible GPS satellites above 10° in elevation.

ON-BOARD GPS SATELLITE SELECTION ALGORITHM

With the 18-satellite GPS constellation, up to nine are visible above the Topex horizon (90° from the zenith). However, the GPS receiver onboard Topex will be equipped with only six independent dual-frequency channels. In other words, signals from only six GPS satellites can be received at any one time. To optimize the tracking data strength, proper selection of six GPS satellites out of the available set is required. Should one or more channels fail, careful satellite selection becomes even more important. There are three criteria that need to be considered. First, switching from one GPS satellite to another should be minimized to maintain data continuity, an important factor for carrier phase data. Secondly, any selected GPS satellite should have common view with at least another selected GPS satellite from both Topex and at least one ground tracking site so that instantaneous elimination of clock error by double differencing is possible. Thirdly, the selected set of GPS satellites should have a low

TABLE 1
ERROR MODEL AND OTHER ASSUMPTIONS
USED IN COVARIANCE ANALYSIS

User Satellite:	TOPEX (1,334 km in altitude)
Number of Stations:	6 (cf. Fig. 1)
Number of GPS Satellites:	18
Cut-off Elevation:	10° at stations 0° at TOPEX
Data Type:	P-code pseudorange carrier phase
Data Span:	2 hours
Data Interval:	5 minutes
Data Noise:	5 cm (pseudorange) 0.5 cm (carrier phase)
Carrier Phase Bias:	10 km (adjusted)
Clock Bias:	3 μsec (adjusted as white process noise)
TOPEX Epoch State:	2 km; 2 m/sec (adjusted)
GPS Epoch States:	2 m; 0.2 mm/sec (adjusted)
Station Location:	5 cm each component
Zenith Troposphere:	1 cm
Earth's GM:	1 part in 10^8
Gravity:	scaled GEM10 – GEML2 (20×20 lumped)
Solar Pressure:	10%

PDOP (Position Dilution of Precision), a measure of performance degradation due to observing geometry. A practical requirement for the GPS satellite selection algorithm for Topex is that it should be sufficiently compact to fit into 2.8 kbytes of the onboard computer memory. The following selection algorithm is developed to meet these criteria.

There are three levels of selection, with increasing complexity. A lower level may be used when all six channels of the Topex receiver are working; higher levels are needed when one or more channels fail.

Level 1: The selection will start with those GPS satellites having the longest remaining view periods. Thereafter any setting GPS satellite will be replaced by the one having the longest remaining view period.

Level 2: In addition, each new GPS satellite selected should have common view with at least one ground station which in turn has at least one other selected GPS satellite in common view with Topex so that doubly differenced data can be formed. This criterion is ignored if the number of eligible GPS satellites is smaller than the number of receiver channels available.

Level 3: In addition, the new set should have a low PDOP value.

A flow chart for the selection algorithm is shown in Fig. 2. The algorithm is made simple by combining the three levels into the calculation of a penalty function. The selection of the proper set of GPS satellites becomes the selection of the lowest value for the penalty function. For Level 3, the penalty function is the square of the weighted PDOP for the selected set of GPS satellites.

$$PDOPSQ = [\ \text{TRACE of last } 3 \times 3 \text{ of } (A^T W A)^{-1}\ ]\ \Delta T$$

where

$$A = \begin{pmatrix} 1 & \cos\alpha_1 \cos\gamma_1 & \sin\alpha_1 \cos\gamma_1 & \sin\gamma_1 \\ 1 & \cos\alpha_2 \cos\gamma_2 & \sin\alpha_2 \cos\gamma_2 & \sin\gamma_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \cos\alpha_{Ns} \cos\gamma_{Ns} & \sin\alpha_{Ns} \cos\gamma_{Ns} & \sin\gamma_{Ns} \end{pmatrix},$$

with α_i and γ_i being the azimuth and elevation angles of the i-th GPS satellite observed, and N_s the number of GPS satellites selected; W is a diagonal matrix with its diagonal elements equal to the remaining view periods and ΔT is the minimum channel switch interval (nominally 5 minutes). For level 1 and 2,

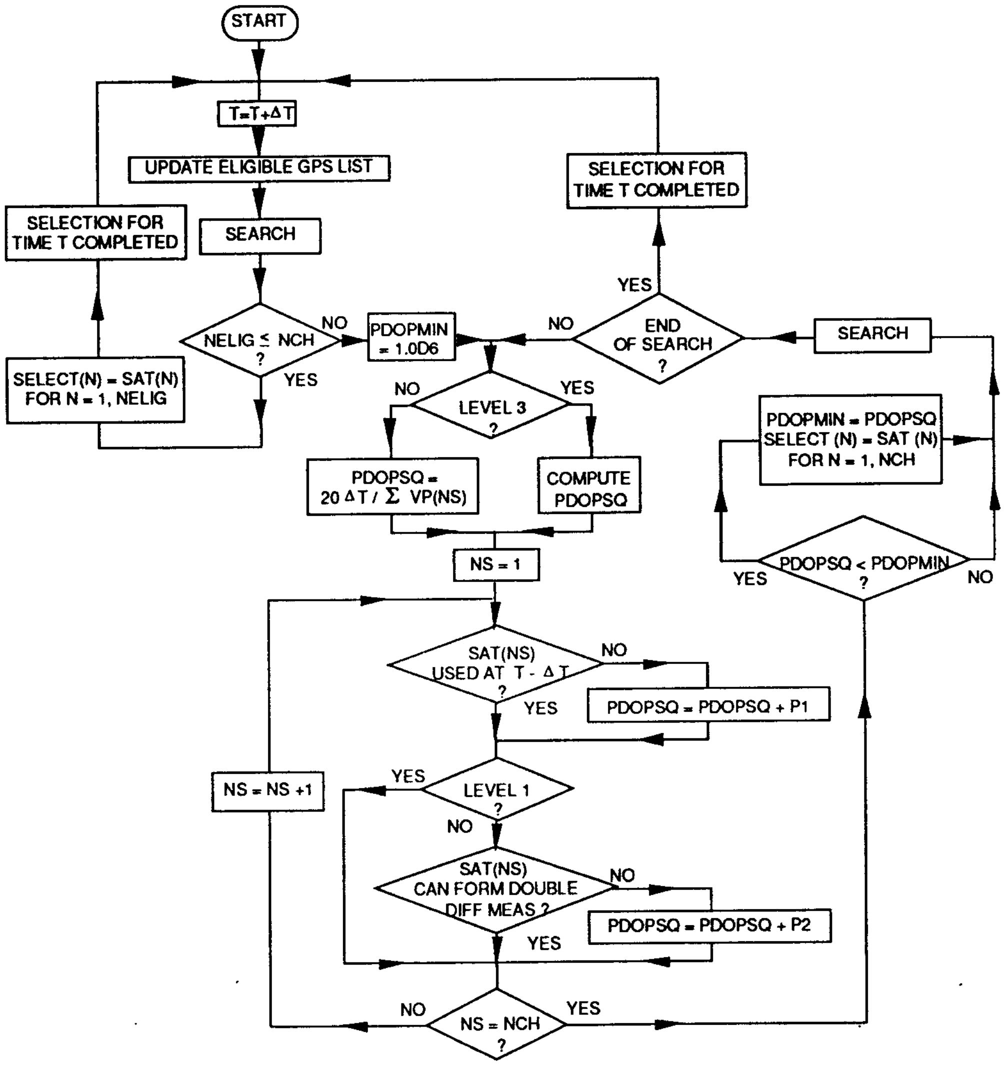
$$PDOPSQ = 20\ \Delta T\ /\ \Sigma\ (\text{remaining view period})$$

where the summation is over N_s. An additional penalty, $P_1 = 10$, is added to $PDOPSQ$ when a switch of channel is made. Another penalty, $P_2 = 200$, is added when a GPS satellite selected cannot form doubly differenced data (not used for Level 1). After all possible combinations of available GPS satellites are tested, the one with the lowest value of $PDOPSQ$ is selected as the proper set to be observed by the onboard receiver.

Because the set of GPS satellites thus selected is the result of a tradeoff between low PDOP and other considerations, it does not in general yield the lowest PDOP. However, under most circumstances the PDOP is only slightly higher than the lowest possible, as shown in Fig. 3.

GPS ANTENNA VIEW ANGLE

A key factor affecting the performance of GPS-based Topex orbit determination is the GPS antenna view angle. Raising the minimum view angle well above the Topex horizon will not only reduce the number of visible GPS satellites but also weaken the observing geometry. On the other hand, GPS signals coming from too low a view angle (say, near or below the Topex horizon) will suffer from large multipath effects, or even total blockage. A simulation over a 2-day period indicates that a cutoff angle of 85° from the zenith (5° elevation) will allow six or more satellites to be visible 55% of the time, five or more 95% of the time, and at least four at all times, as shown in Fig. 4. If a full hemispherical field of view (0° cutoff elevation) is available, there will be at least five GPS visible at all times and not fewer than six 87% of the time. On the



T: CURRENT TIME

ΔT: SWITCH INTERVAL

NELIG: NUMBER OF ELIGIBLE (VISIBLE) GPS

NCH: NUMBER OF CHANNELS

NS: CHANNEL NUMBER (1 — NCH)

SAT(NS): SEARCHED GPS SET

SELECT(NS): SELECTED GPS SET

VP(NS): REMAINING VIEW PERIOD

P1, P2: PENALTIES (P1 = 10, P2 = 200)

SEARCH: SUBROUTINE FOR SEARCING ALL POSSIBLE COMBINATIONS OF GPS

Fig. 2. GPS selection algorithm for Topex receiver

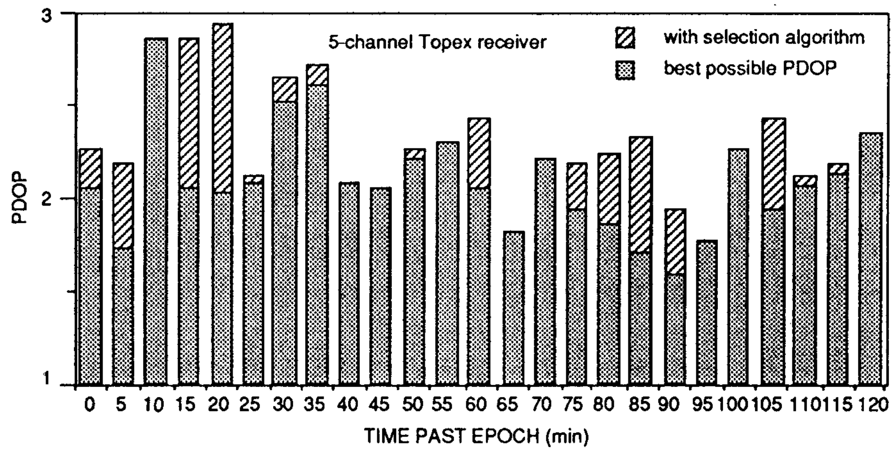


Fig. 3. Increase of PDOP with GPS selection algorithm

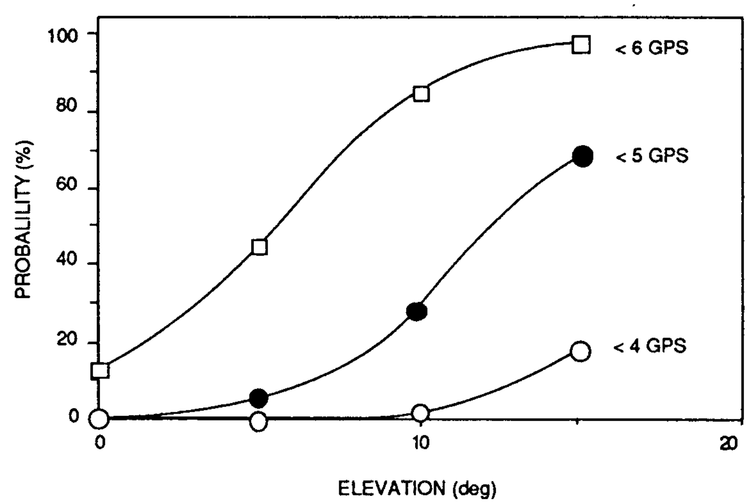


Fig. 4. Probability of fewer than 4, 5, and 6 GPS satellites visible from Topex with different cutoff angle

other hand, a cutoff angle of 80° from zenith will allow fewer than 5 GPS satellites to be visible about 30% of the time.

The performance of Topex orbit determination with different cutoff view angles, as predicted by a covariance analysis, is shown in Fig. 5 for a Topex receiver with 5-channel capability. The multipath effects are ignored in this analysis. When the minimum elevation angle is raised from 0° to 5° the error in Topex altitude increases

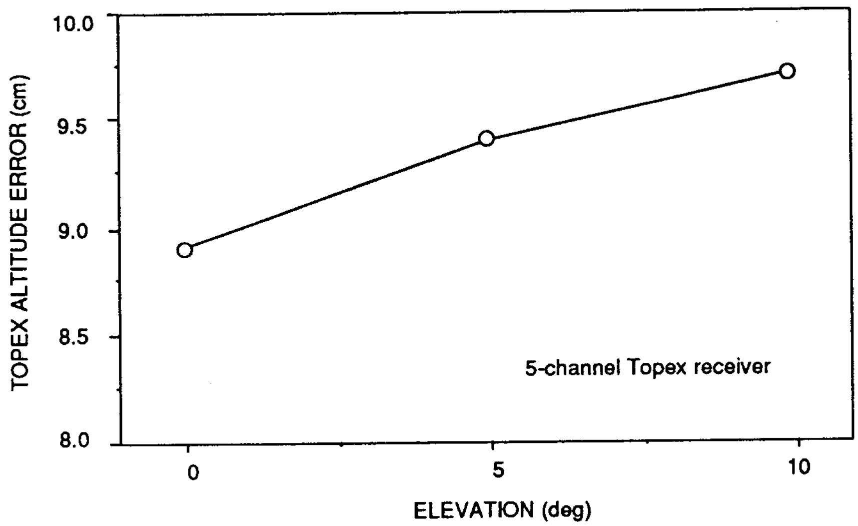


Fig. 5. Comparison of performance with different view angle limits

only marginally (from 8.9 to 9.4 cm). Further increasing the minimum elevation angle to 10° again increases the error by an insignificant amount despite there being fewer than 5 GPS satellites in view about 30% of the time. This is because the reduced-dynamic technique tends to rely more heavily on the dynamic information whenever the geometry is poor, thus smoothing overall error.

GROUND TRACKING NETWORK CONFIGURATION

In addition to establishing an earth-fixed coordinate system, ground tracking sites help to reduce GPS clock, instrumental and ephemeris errors as mention above. The three DSN sites will be equipped with the newly developed high-performance Rogue GPS receivers (Ref. 8) and form the minimum ground tracking network. Clearly, a larger network will mean larger maintenance and data processing cost; however, complementary tracking sites at other parts of the world are needed to broaden the geographical coverage and hence increase the data strength. Earlier analyses have focused on using a six-site ground network. Here, an analysis with the three DSN sites alone is compared with a six-site solution to illustrate the value of the added sites.

Although up to 9 GPS satellites are visible from Topex and each of the ground receivers, the number of GPS satellites visible that can form double differences between Topex and the ground measurements can be as few as zero depending on the number of ground sites used. Fig. 6 compares, for 3-site and 6-site networks, the points along a 2-day Topex ground track where 4 or more GPS satellites can form double differences. Note that the 6-site network provides nearly full global coverage while the 3-site network leaves a large area uncovered. The histogram in Fig. 7 shows that, with the 6-site network, 6 or more GPS satellites can form double differences about 84% of the time, and never will there be fewer than 4; with the 3-site network there are no more than 5 GPS satellites involved for about 84% of the time, and at times no double difference can be formed from any of the visible GPS satellites.

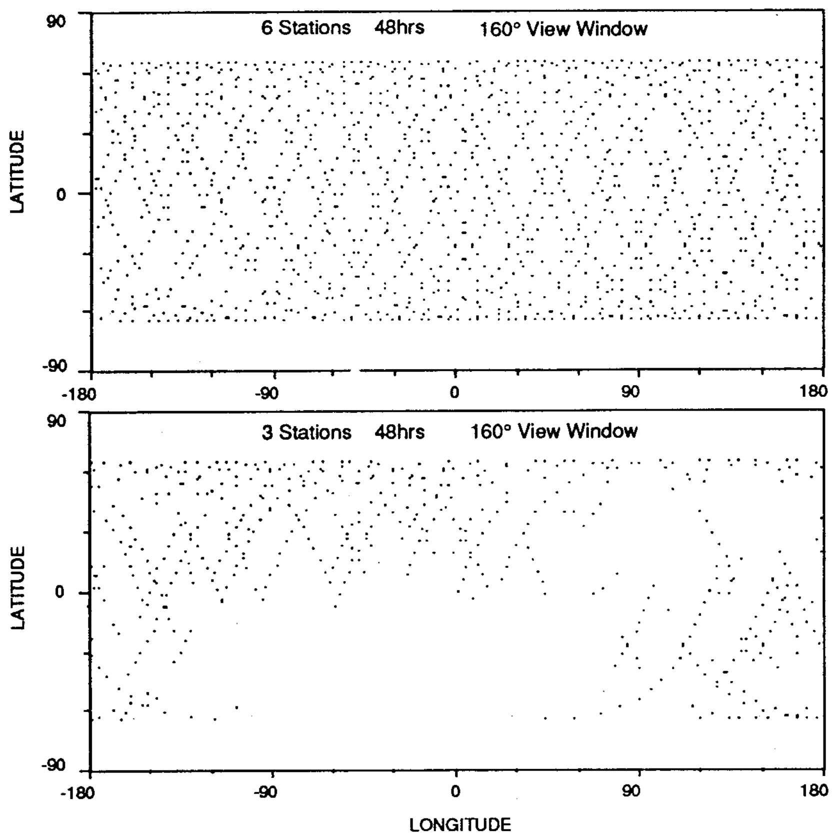


Fig. 6. Two-day coverage of Topex ground track where 4 or more GPS satellites observed can form double difference

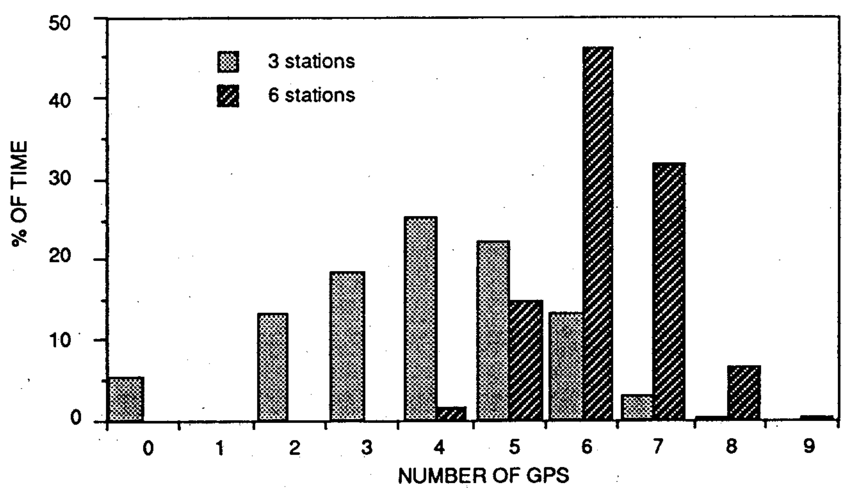


Fig. 7. A histogram of the number of GPS satellites that can form double difference measurements between Topex and ground tracking sites

Fig. 8. compares the performance between the two networks based on the results of a covariance analysis. As expected, the RMS (over a 2-hr period) Topex altitude error with the reduced network is far poorer (by more than a factor of 2) than with the full six-site network. The poor regional coverage results in occasional high error in Topex altitude determination, as can be clearly seen in Fig. 9 for a 5-channel Topex receiver.

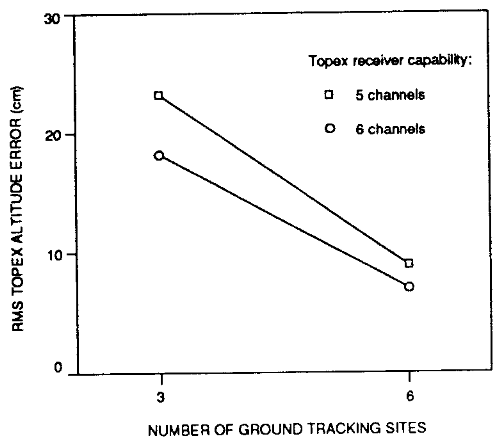


Fig. 8. Comparison of Topex altitude determination performance between a 3-site and a 6-site networks

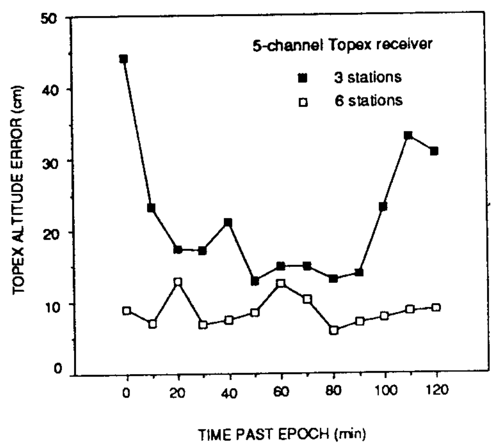


Fig. 9. Topex altitude determination errors using a 3-site and a 6-site networks over a 2-hr period

REDUCTION OF MULTIPATH EFFECTS

Ground-based GPS demonstrations carried out over the past few years have indicated that multipath is a major limitation to accurate pseudorange data. Currently, the thermal noise on the pseudorange measurement of a well-designed GPS receiver is one or two centimeters after a few minutes of averaging (Ref. 8). However, error due to multipath can be as high as several meters. Means to reduce the multipath effects have been investigated. One approach which has proved effective in reducing multipath around ground receivers is placing a GPS antenna in a conducting backplate made up of concentric choke rings (Ref. 9).

The major source of multipath for the Topex flight receiver is the reflected signals from the TDRSS (Tracking and Data Relaying Satellite System) high-gain antenna, the solar panels, and the spacecraft body, as shown in Fig. 10. The effects of multipath on pseudorange measurements will depend on the gain pattern of the GPS antenna and where it is placed with respect to these surfaces. A simple approach to reducing Topex multipath is to elevate the GPS antenna on a boom to keep it well above all reflecting surfaces, while employing a backplate to minimize gain in the direction of the reflected signals.

To assess the multipath effects on GPS pseudorange measurements at Topex a software simulator is being developed. With this new analysis tool, the GPS antenna can be placed at arbitrary heights above the Topex instrument module, and signals reflected from the solar panels, the instrument module, the high-gain antenna, and the attitude control module, as well as the direct GPS-to-Topex signals, can be simulated. The Topex attitude and the orientation of the solar array and of the high-gain antenna are all modeled. The measured radiation pattern of a cross-dipole antenna with a choke-ringed backplate is used. Preliminary results of the analysis indicate that when the antenna is raised to a height of 4.3 m above the top face of the instrument module (1.5 m above the top of the TDRSS antenna) the multipath signals can be greatly reduced, as shown in Fig. 11, where the strength of multipath signals from different reflecting objects is compared with that of the direct signals for three different GPS antenna heights, *h*. These results clearly show that the multipath effects on Topex GPS pseudorange measurements can indeed be reduced with proper placement of the onboard GPS antenna.

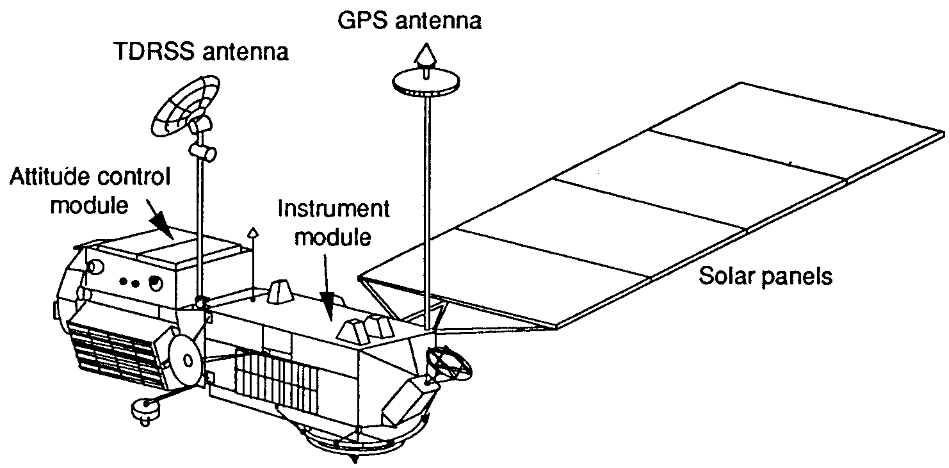


Fig. 10. Topex/Poseidon spacecraft

CONCLUDING REMARKS

Precision Topex altitude determination using differential GPS techniques requires careful design and placement of the Topex onboard antenna, proper siting of the ground tracking network, intelligent satellite selection and an effective estimation scheme. While earlier analysis has indicated that the reduced-dynamic technique is the ideal estimation technique, this paper has focused on other important considerations in achieving decimeter orbit determination. A GPS satellite selection algorithm has been developed. The algorithm is compact enough to fit in the limited onboard computer memory while still selecting a near-optimal set of GPS satellites to observe. The selected set will have reasonably long passes for continuous carrier phase measurements, common visibility with ground tracking sites for double differencing, and low PDOP for good geometrical strength.

The current analysis has shown that a ground tracking network comprising the three NASA DSN stations alone does not provide good global coverage. With this three-site network Topex altitude can be determined only to about 20 cm. Adding

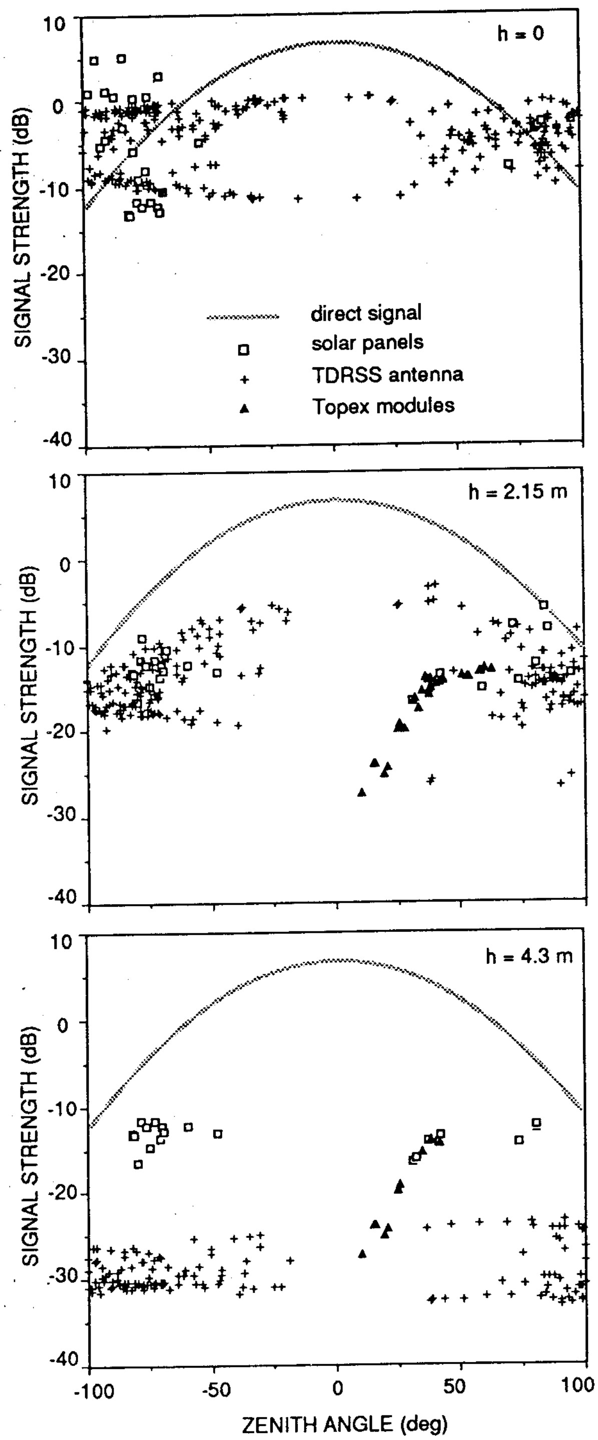


Fig. 11. Reduction of Topex multipath signals by raising the GPS antenna

three complementary sites improves performance dramatically. With the six-site network Topex altitude error is reduced below 10 cm. GPS signals incident from an angle too close to the Topex horizon (0° elevation) or lower will suffer from strong multipath effects. Raising the elevation cutoff angle from 0° to 10° to suppress multipathing has only a slight effect on overall solution strength. Hence, the view window may be narrowed to 160° to reduce the multipath effects on the Topex received signals. Multipath error can be further reduced by raising the GPS antenna above the reflecting objects using a boom. Further analysis and simulation are needed to better understand the characteristics and reduction of multipath effects.

ACKNOWLEDGMENT

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