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SINGLE ARC TRACKING ERRORS ASSOCIATED WITH ALTIMETER MEASUREMENTS

GEOS-B C-BAND SYSTEM

PROJECT GROUP

AND

WOLF RESEARCH & DEVELOPMENT

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Status Report

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1.0 INTRODUCTION

Scientists and NASA program management personnel have identified program objectives that include the development of satellite altimetry as instrumentation for solid-earth and ocean physics studies. Currently efforts are underway to plan the first system to be flown on GEOS-C scheduled to be launched in late 1971.

Both instrument design and experiment planning personnel have developed an increasing interest in the present and projected capabilities of satellite positioning systems. This interest can be further understood in terms of the accuracy, precision, resolution and validation testing decisions facing the personnel involved in the various phases of this project.

Wallops Station personnel have obtained practical hardware and software experience related to satellite positioning in the GEOS-B C-Band project. The GEOS-C Satellite will closely resemble the GEOS-B in orbital dynamics and will utilize essentially the same type tracking systems. Therefore it was decided that with little effort some practical projection of the present tracking system errors into the altimeter measurement geometry could be made available for everyone's use. The primary object of this study is to investigate the accuracies of orbit determinations in the radial coordinate utilizing currently available tracking systems. The results pinpoint certain areas which are critical for the efficient utilization of altimeter measurements.

The ORAN orbital simulation program, currently operational at Wallops Station, contains the capability necessary for computing radar coordinate errors and was therefore used in the altimeter study discussed in this report. This program simulates the minimum variance orbit determination process and calculates the accuracy of the orbit obtained with any specified amount of orbital tracking data. The calculation of the variance of the estimated orbit is broken down into contributions from measurement noise and from systematic errors such as measurement biases. The effects of the latter type error are computed separately for each such error.

2.0 TECHNICAL APPROACH

Satellite orbits may be determined using almost any quanity of tracking data. For example, an orbit can be determined using data from a single satellite pass over one radar tracking station. An orbit can also be determined using data of different types from many stations for many satellite revolutions. Orbits determined by these two procedures will, of course, not be the same. Indeed, their errors will have different characteristics.

Orbits determined from many revolutions of tracking data will have periodic errors, which may be quite large (100 meters or more), due to geopotential model errors. Depending upon the distribution of tracking stations, the orbit errors may or may not be small in the vicinity of a particular tracking station. Studies have shown that the mean orbit error tends to be small during a pass over a station; however, variations in errors may be greatest in this vicinity [1]. Such orbits may present problems as a reference for altimeter data.

At the other end of the spectrum, single pass type solutions can have small errors in the vicinity of the tracking station(s), although errors may be many hundreds of meters on the opposite side of the orbit. As an initial approach, the present study has considered the characteristics of orbits as determined using a single satellite pass. Both "single-station" and "three-station" C-Band radar tracking of the GEOS-C satellite have been considered.

There are two essential logic steps to be considered in performing orbital error analyses to insure that the simulations will closely approximate realistic conditions. The first is to insure that the

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[1] Error Sensitivity Function Catalog, C.F. Martin, J.R. Vetter, Wolf Research and Development Corporation report prepared for National Aeronautics and Space Administration, Publication pending.

errors selected for the simulation process are reasonable estimates of the performance characteristics of the system. This requires an in-depth knowledge of the tracking systems and experience in handling and reducing the data from these systems. Based upon our experience with GEOS-B, we are certain that the noise and systematic error estimates selected for these analyses represent reasonable, if somewhat conservative, estimates of the errors which may be encountered from a well calibrated and operated C-Band radar. The second factor is the necessity to propagate these system errors into the radial orbit component (H) in the same manner in which they would be propagated by an actual orbit determination. In addition, in order to evaluate the capability of an altimeter to perform relative profiling, it is necessary to understand how the various errors distort the profile. Typically, error contributions take the form:

Total Uncertainty = Noise + individual unmodeled errors (appropriately combined).

Unfortunately, the criterion of total orbit uncertainty is not sufficient to define the profile error problem. The total orbit uncertainty may considerably exceed the magnitude of the effects which we wish to observe. For this reason it is necessary to calculate the type of trending which each unmodeled error can induce into the orbit. For example, an unmodeled error could cause a pure bias in H which would not affect the altimeter determination of the ocean profile. Another type of unmodeled error, giving the same value as the first for total uncertainty, could trend H and seriously distort the profile. All of these calculations are properly performed in the ORAN program.

The orbital simulations are discussed in detail in Section 2.1 for a single-radar solution and in Section 2.2 for a three-radar solution. In neither case are errors propagated in drag and solar radiation pressure models since previous work on GEOS type satellites has shown these effects to be negligible for arc lengths much longer than are being investigated here. The same is true for radar dynamic errors such as servo lag. The dynamics of the satellite are such that these errors are negligible for GEOS type passes. It has been assumed that the satellite dynamics have been analyzed and that the radar set-up (servo bandwidths, pulse widths, etc.) has been matched for these missions.

The estimates of the station survey errors are based on expected center-of-mass uncertainties rather than the possibly smaller, relative uncertainties one might propagate for interconnected stations on a single datum. Since, in general, there can be multiple station tracking from both groups of interconnected datum stations and stations on independent datums, it was decided to propagate "worst case" conditions. Since Antigua and Grand Turk are on the same datum, this fact should be taken into account when interpreting the three-station results. The 15-meter uncertainty used in these analyses represents an estimate of the center-of-mass uncertainties which should be achieved shortly for the C-Band tracking network, although the ultimate goal for C-Band positioning is 10 meters or better relative to the center-of-mass.

In both orbital simulations, essentially no a priori information was assumed for the orbital elements, since only the C-Band radar data from the stations simulated is assumed to be available. Any additional orbital information from a world wide network would be expected to be either too weak to help the solution or sufficiently contaminated by geopotential errors to seriously degrade the solution.

The present analysis of the effects of satellite orbit errors on altimeter measurements is by no means comprehensive. The method of approach is, however, applicable to somewhat different methods of determining the satellite orbits. In addition, the results obtained lead to several important conclusions and suggest future simulations which should be investigated.

2.1 SINGLE-STATION ORBIT SIMULATION

A single-station orbit simulation was made to determine effects of tracking system errors on the H component of the orbit when a single station provides satellite tracking in the immediate area of the altimeter evaluations. For example, this would be the case when altimeter measurements are made over the Indian Ocean. C-Band tracking would then be available from Tananarive on the western side and Carnarvon on the eastern side with no overlapping tracking from either station. The simulations were based on the following orbit:

Epoch time: 04 February 1971, 15 hrs. 42 min. 41 sec.

Inertial Elements at Epoch:

$X = 2{,}101{,}391\text{m}$, $Y = -7{,}349{,}676\text{m}$

$Z = 2{,}136{,}248\text{m}$, $\dot{X} = 6{,}452.779\text{m/sec}$,

$\dot{Y} = 2{,}211.810\text{m/sec}$, $\dot{Z} = 1{,}487.497\text{m/sec}$

These elements are based on nominal orbit values given for the GEOS-C Satellite with inclination of 20°. The *a priori* epoch element variance covariance matrix is as follows:

$\sigma_X = 1\times10^{12}$ $\sigma_Y = 1\times10^{12}$ $\sigma_Z = 1\times10^{12}$

$\sigma_{\dot{X}} = 1\times10^{6}$ $\sigma_{\dot{Y}} = 1\times10^{6}$ $\sigma_{\dot{Z}} = 1\times10^{6}$

Radar Noise Values:

$\sigma_R = 2$ meters

$\sigma_A = 20''$ arc

$\sigma_E = 20''$ arc

Radar Tracking Station: Antigua FPQ-6 with a 10° elevation angle cutoff

Length of Error Propagation: 35 minutes

The effects of the following "unmodeled" errors are propagated in this solution:

Antigua Range (R) Bias = 5 meters
Antigua Azimuth (A) Bias = +0.1 milliradians ≈ 21" arc
Antigua Elevation (E) Bias = +0.1 milliradians ≈ 21" arc
Antigua Timing Bias = +1 milliseconds
Antigua Refraction Error = 10% of nominal correction
Antigua X (Long) Error = +15 meters
Antigua Y (Lat) Error = +15 meters
Antigua Z (Hgt) Error = +15 meters
Gravity Model Error = 100% of the difference in terms of the SAO-M1 and SAO-69 gravity model up to and including 8,8.
GM Error = $1:10^6$

Figure 1 shows the satellite ground track and the amount of tracking obtained from Antigua with the 10° elevation angle cutoff constraint. The maximum elevation angle from Antigua is approximately 78.5 degrees. The length of tracking time is approximately 17 minutes. Figure 2 is a plot of the uncertainty in the H component of the orbit versus time, propagating <u>only</u> the noise values for the radar. This represents the best available solution for a pass of this type with tracking from a single radar whose noise values are as shown above and with all systematic errors negligible. Figure 3 is a plot of the uncertainty in the

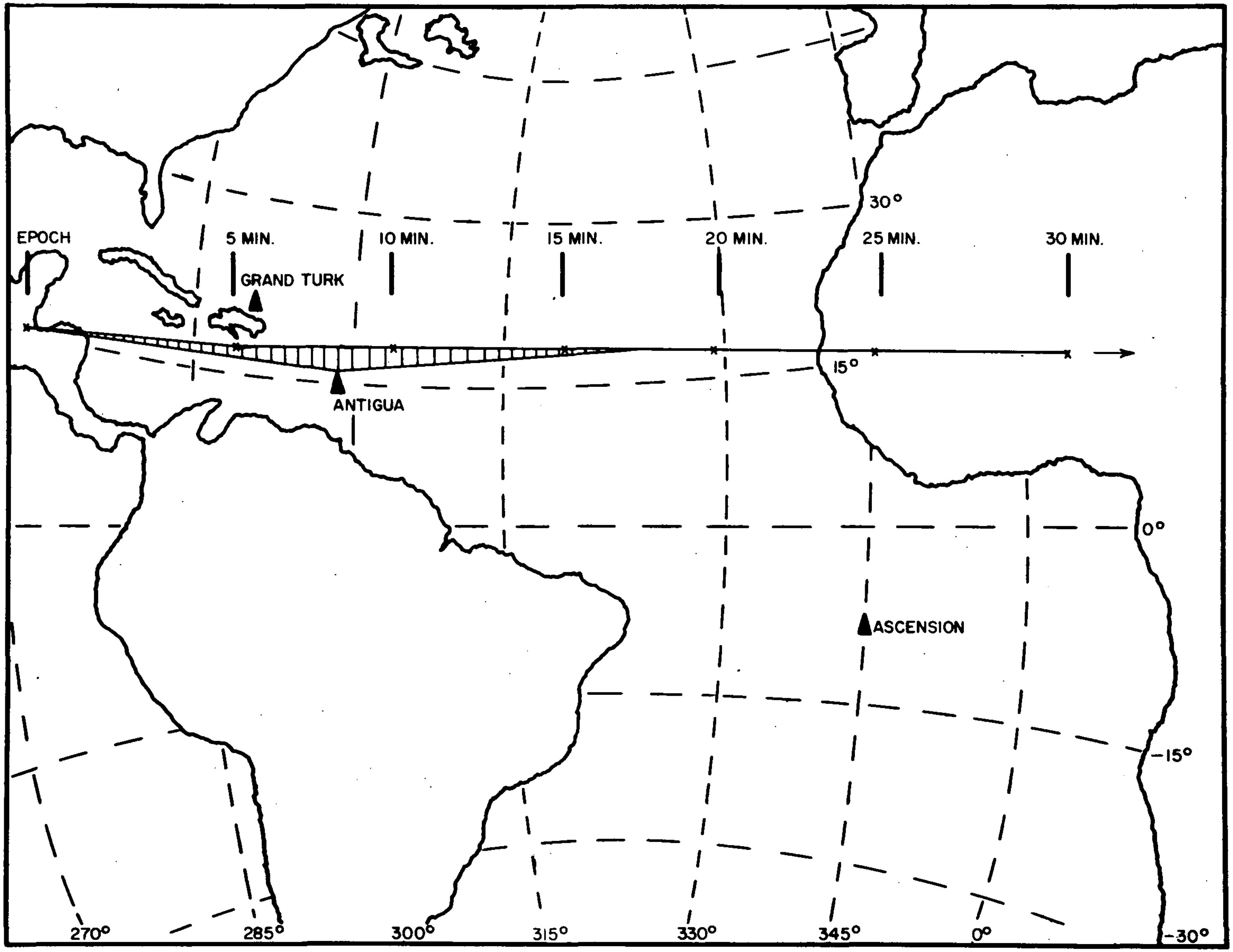


FIGURE 1

SATELLITE GROUND TRACK
ANTIQUA TRACKING

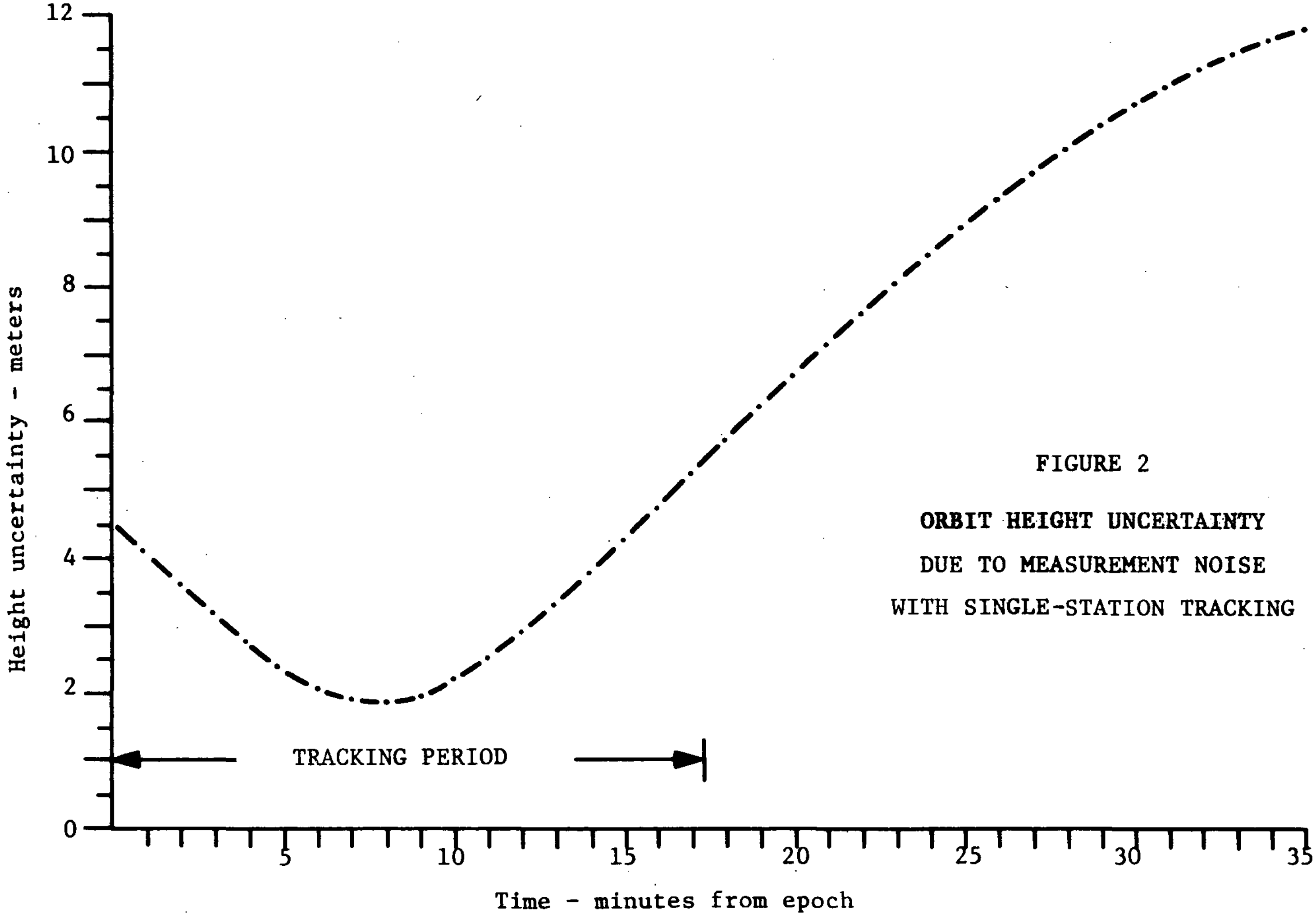


FIGURE 2

ORBIT HEIGHT UNCERTAINTY
DUE TO MEASUREMENT NOISE
WITH SINGLE-STATION TRACKING

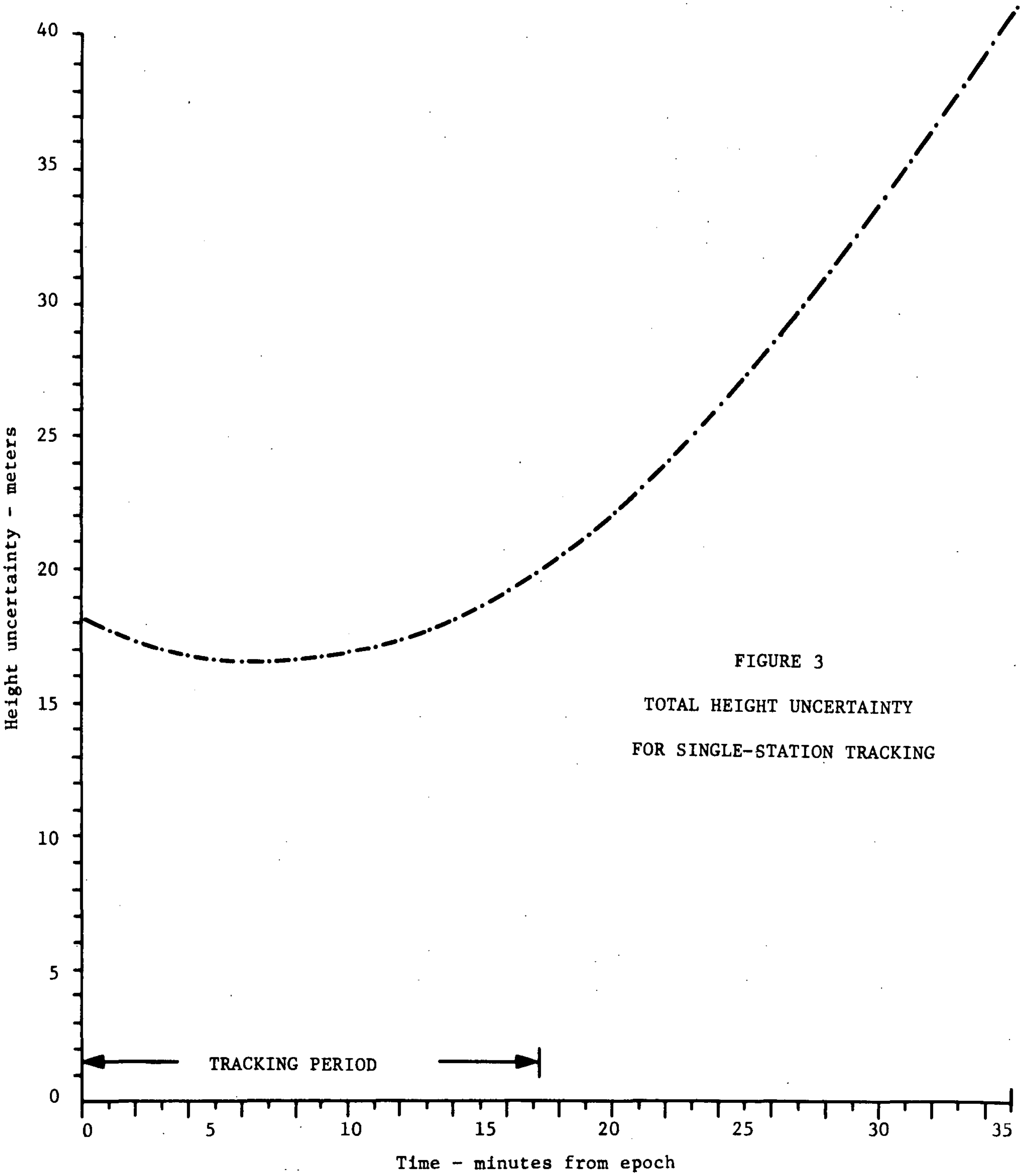


FIGURE 3

TOTAL HEIGHT UNCERTAINTY

FOR SINGLE-STATION TRACKING

H component of the orbit vs time including the effects of the noise plus unmodeled errors. When, as is the case here, the magnitudes of the unmodeled errors represent valid estimates of real conditions, the uncertainties here represent the actual conditions which will be encountered during the experiment. Since the ORAN program shows the effects of each individual unmodeled error, an investigation can now be made as to which of these errors are the major contributors to the H uncertainty. In Figure 4 the effect of various errors on the H component can be seen. The plots now show exactly what the effect of the error is on H so that sign convention is now applicable. For example, the effect of a +5 meter range bias would affect H from -6 to -20 meters during 27 minutes of the pass. The effects of the errors are also scalable so that, for example, if the height error at Antigua were to be 5 meters rather than 15 as shown, the effects on H can be scaled by 1/3. Figure 4 is a plot of the largest contributors to the H uncertainty. For clarity those unmodeled errors which have small effects on H have not been plotted. The RSS of these individual errors is a close approximation to the H uncertainty shown in Figure 2. It can be seen that some of the unmodeled errors cause a "warping" of H of almost 1 meter per minute even during the tracking period. This effect could be more serious than a straight biasing effect when altimeter profiling is taking place since the "zero reference" (orbital H) will be quite trended as well as biased.

It should be pointed out that the program also propagates the effects of noise and unmodeled errors on the along track (L), cross track (C), and total position (P) components of the orbit. In this case, as is to be expected, the azimuth errors propagate primarily into the L component. The largest error in L is approximately 600 meters and in C it is approximately 100 meters. Since these are well within the altimeter footprint (7 nautical miles), they are not considered to be significant for relative profiling.

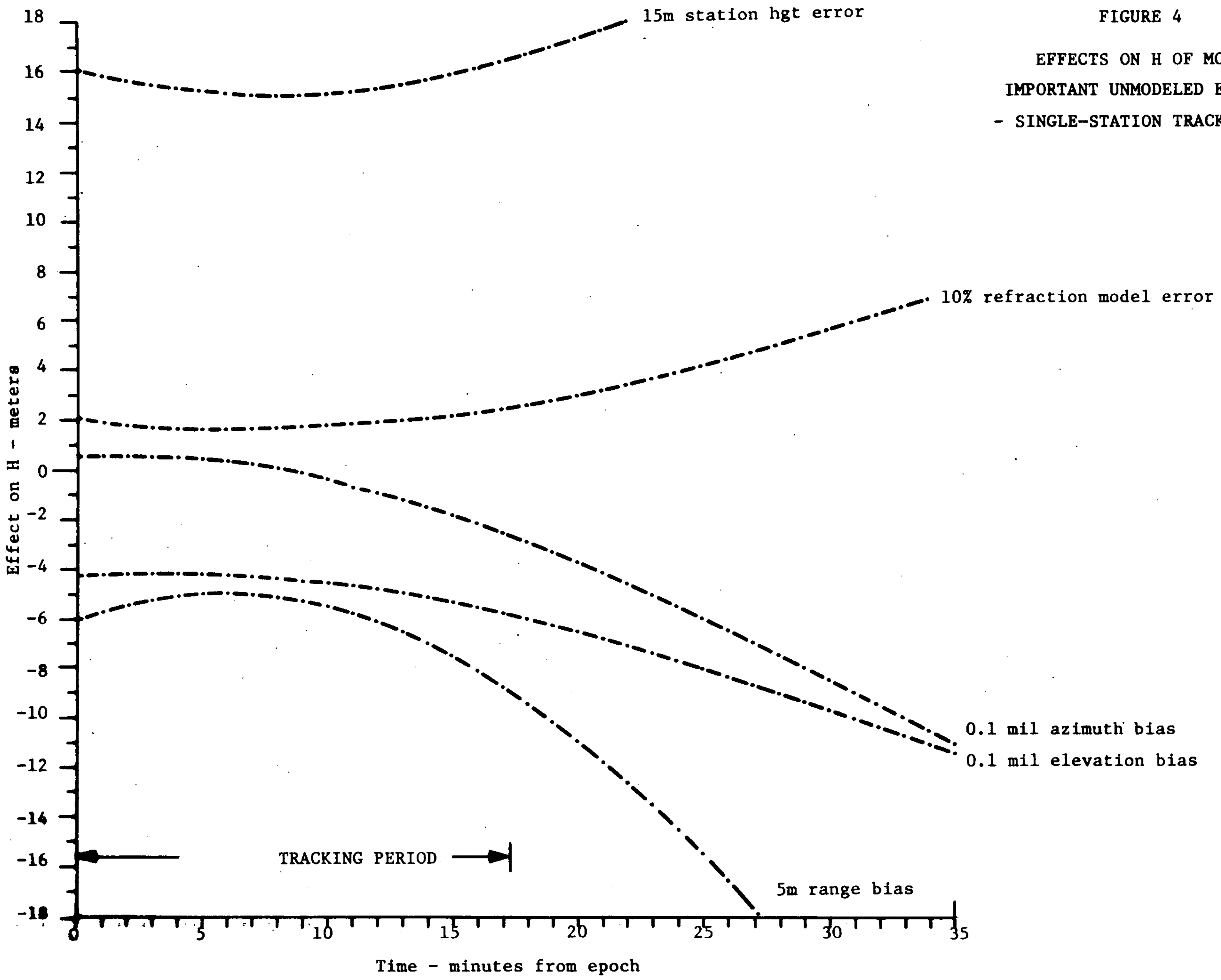


FIGURE 4

EFFECTS ON H OF MOST
IMPORTANT UNMODELED ERRORS
- SINGLE-STATION TRACKING -

2.2 THREE-STATION ORBIT SIMULATION

An orbit simulation was made to determine the effects of tracking system errors on the H component of the orbit when three stations are tracking the satellite at various times in the pass. Multiple-station tracking will probably be the normal mode of operation in the Pacific and Atlantic Ocean areas where there is a higher concentration of C-Band tracking stations. In this run we have selected the same orbit as in the single-station run and have added Grand Turk and Ascension as tracking stations. The assumptions for this simulation are as follows:

Epoch time: 04 February 1971, 15 hrs. 42 min. 41 sec.

Inertial Elements at Epoch:

$X = 2{,}101{,}391\text{m}$, $Y = -7{,}349{,}676\text{m}$

$Z = 2{,}136{,}248\text{m}$, $\dot{X} = 6{,}452{,}779\text{m/sec}$

$\dot{Y} = 2{,}211.810\text{m/sec}$ $\dot{Z} = 1{,}487.497\text{m/sec}$

The a priori Epoch Element Variance Covariance Matrix:

$\sigma_X = 1\times10^{12}$ $\sigma_Y = 1\times10^{12}$ $\sigma_Z = 1\times10^{12}$

$\sigma_{\dot{X}} = 1\times10^{6}$ $\sigma_{\dot{Y}} = 1\times10^{6}$ $\sigma_{\dot{Z}} = 1\times10^{6}$

Radar Tracking Stations: Antigua (FPQ-6), Grand Turk (FPQ-6), Ascension (TPQ-18) with 10° elevation angle cutoff

Radar Noise Values: $\sigma_R = 2$ meters (all stations)

Length of Error Propagation: 35 minutes

The effects of the following "unmodeled" errors are propagated in this solution:

Range Bias (All Stations) = +5 meters
Refraction Error (All Stations) = 10% of nominal correction
Timing Error (All Stations) = 1 millisecond
X Survey (All Stations) = +15 meters
Y Survey (All Stations) = +15 meters
Z Survey (All Stations) = +15 meters
Gravity Model Error = 100% of the difference in terms of the SAO M-1 and SAO-69 Gravity Model up to and including 8,8.
GM Error = $1:10^6$

In this run a range only solution is simulated since the contribution of the angles has been proven to be minimal.

Figure 5 shows the satellite ground track and the amount of tracking obtained from the three tracking stations. As can be seen, Antigua and Grand Turk track the satellite simultaneously from near epoch to approximately 15 minutes from epoch. Antigua continues to track alone an additional 2 minutes, and Ascension tracks from 21 minutes to 29 minutes from epoch. Figure 6 shows the effects of radar noise on the uncertainty in the H component of the orbit. The uncertainty is a minimum at approximately the center of the Antigua/Grand Turk tracking span and grows almost linearly to the end of the arc. Figure 7 shows the effects of both noise and the unmodeled errors on the uncertainty in the H component of the orbit. Except for the increase in magnitude, the effects are similar in shape to the noise only effects, with the minimum occuring during the mid point of the Antigua/Grand Turk tracking and growing almost linearly to the end of the arc. The next series

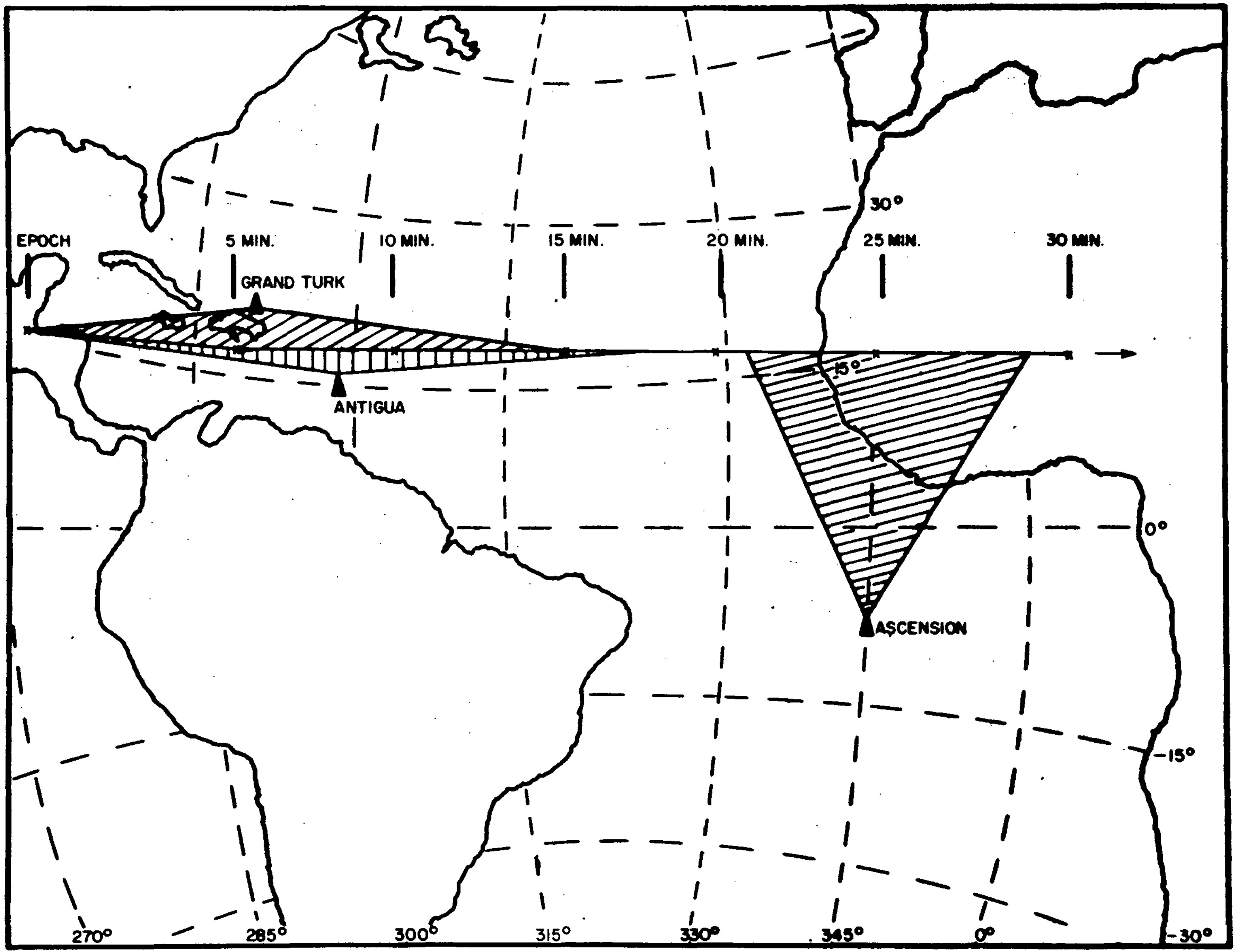


FIGURE 5

SATELLITE GROUND TRACK
THREE STATIONS TRACKING

FIGURE 6

ORBIT HEIGHT UNCERTAINTY

DUE TO MEASUREMENT NOISE

WITH THREE-STATION TRACKING

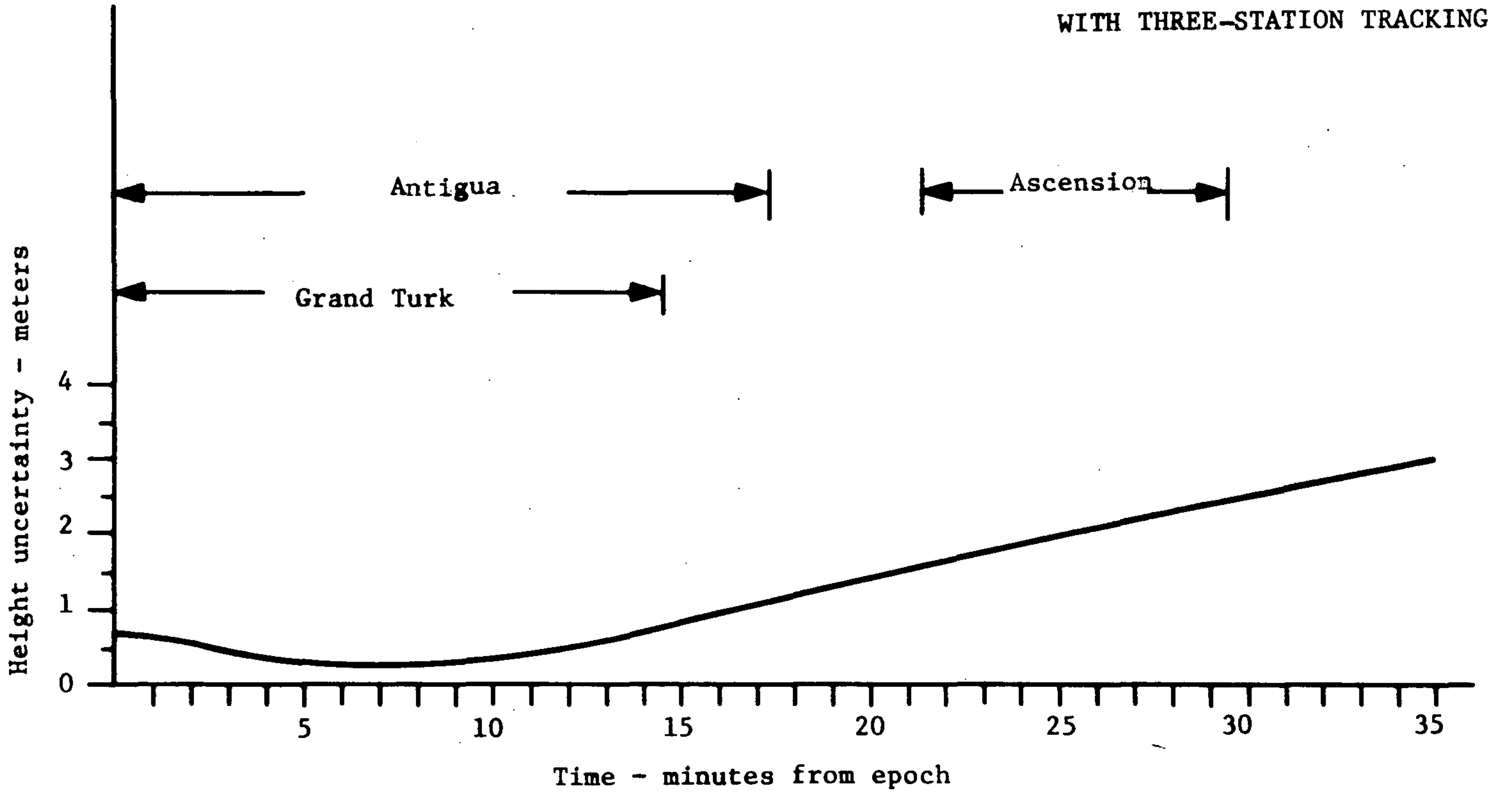
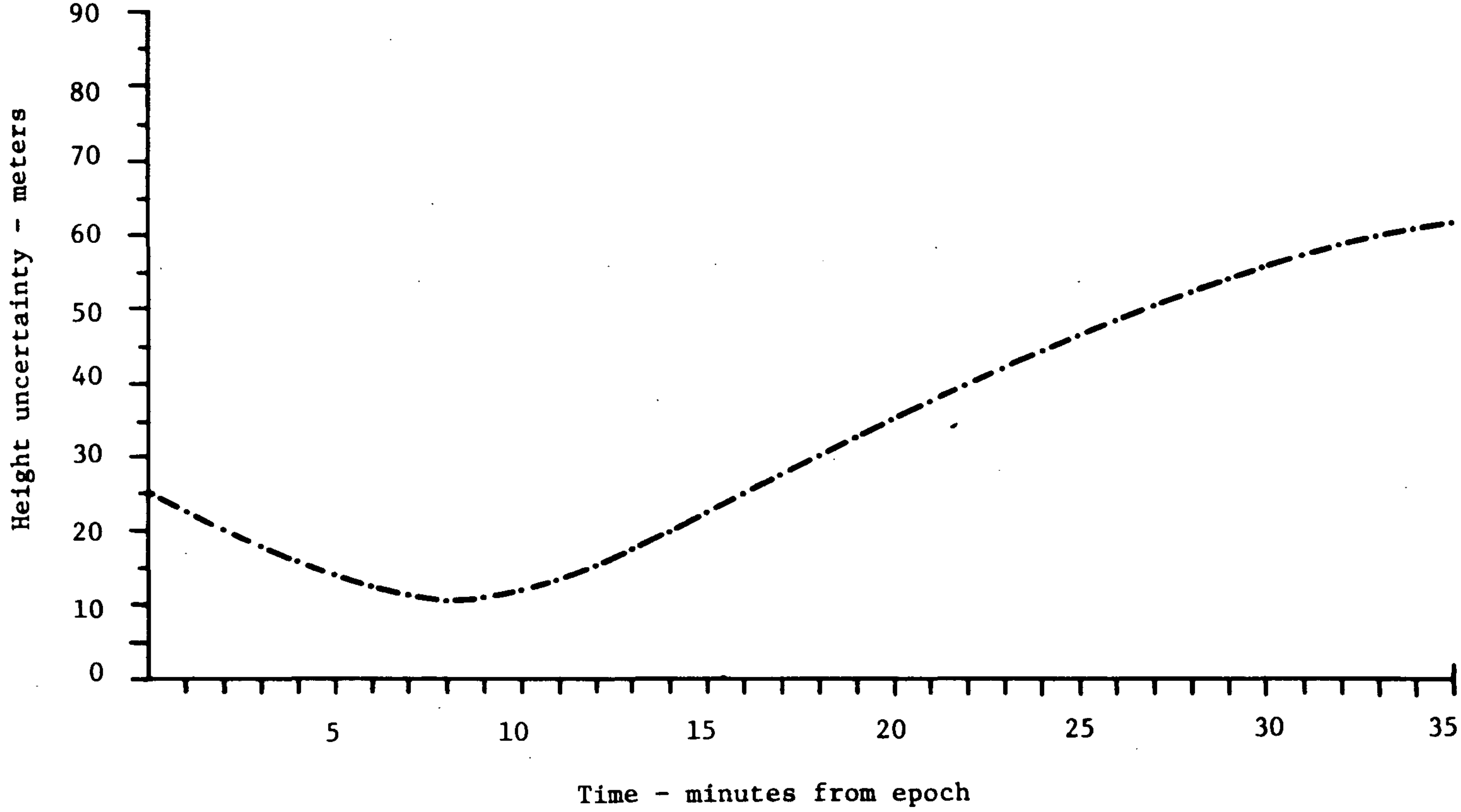


FIGURE 7

TOTAL ORBIT HEIGHT UNCERTAINTY

- THREE-STATION TRACKING -



of Figures demonstrate the effects on H of the individual unmodeled errors. In the interest of clarity, only the major contributors have been plotted. Figure 8 is a plot of the effect of a 5-meter range bias from each of the tracking stations on H as a function of time. For this pass geometry, a range bias at Grand Turk would have a significant effect on the determination of H. The Grand Turk bias would have a tendency to "warp" H as much as .8meters/minute even when Grand Turk and Antigua are tracking simultaneously.

Figure 9 shows the effects of a +15-meter latitude error at each station on H. The maximum error rates here due to an individual station are on the order of .4m/minute. If we take into account, however, the fact that the station latitude errors, particularly for Antigua and Grand Turk, are rather highly correlated, then we must add algebraically (for complete correlation) the effects for the three stations. For complete correlation the net effect is less than .1m/minute.

Figure 10 shows the effects of a +15-meter longitude error at each station on H and the maximum rates here are in excess of 1m/minute. However, a high correlation in the longitude errors at the three stations, as is definitely the case between Antigua and Grand Turk, would reduce the net effect to a quite low value.

Figure 11 shows the effects of 15-meter height errors at each station on H. Again, the station errors are not completely uncorrelated. Note, however, that during the first 10-minute period the Ascension height error has a very small effect but the combined Grand Turk and Antigua effects vary from 24m to 12m over this period in an approximately linear manner. The net variation is then still almost 1m/minute.

FIGURE 8

EFFECT OF A 5-METER
STATION RANGE BIAS ON THE
ORBIT HEIGHT COMPONENT
- THREE-STATION TRACKING -

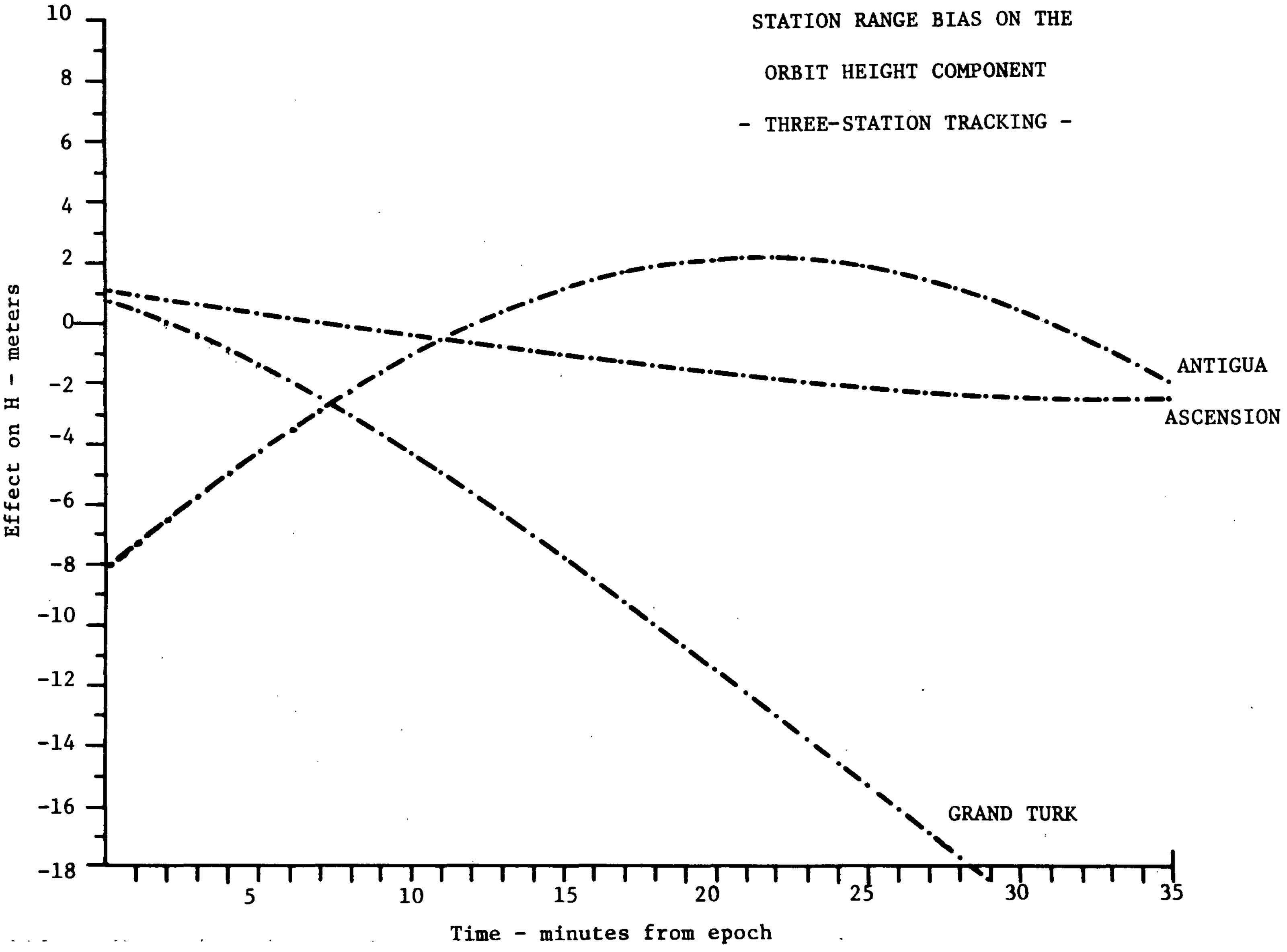


FIGURE 9

EFFECT OF 15-METER STATION
LATITUDE ERROR ON ORBIT
HEIGHT COMPONENT
- THREE-STATION TRACKING -

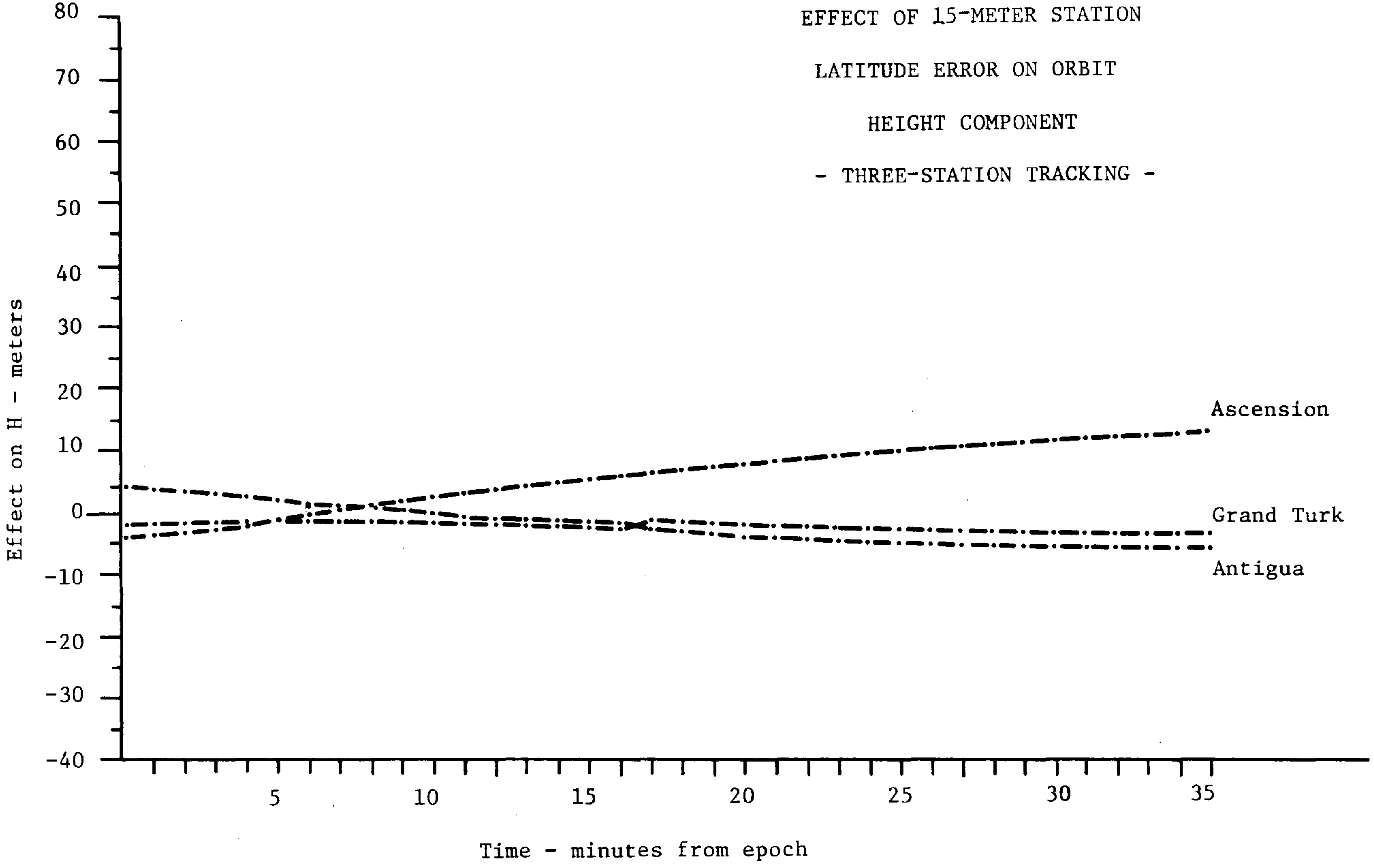


FIGURE 10

EFFECT OF 15-METER STATION

LONGITUDE ERROR ON ORBIT

HEIGHT COMPONENT

- THREE-STATION TRACKING -

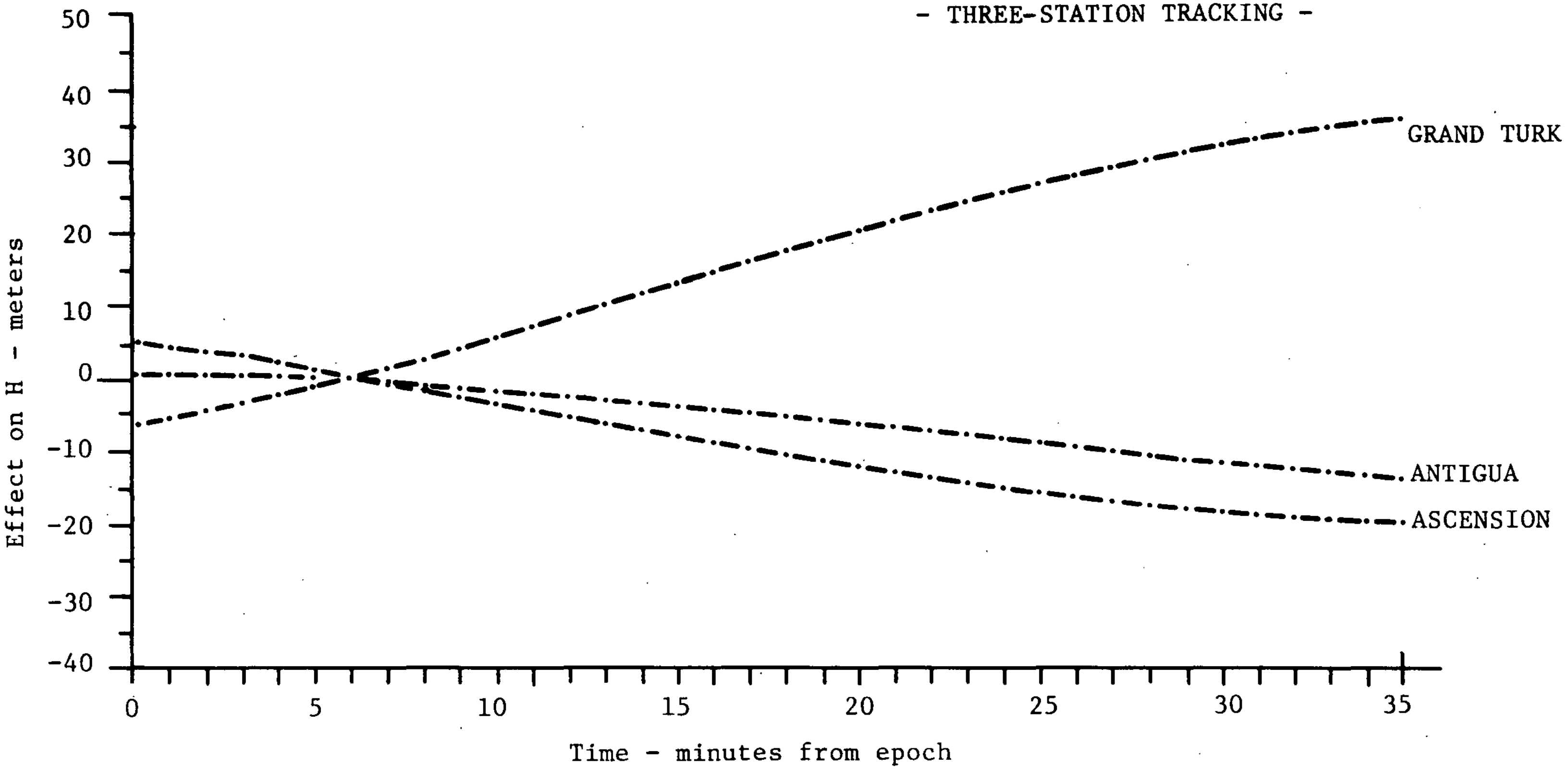


FIGURE 11

EFFECT OF 15-METER STATION

HEIGHT ERROR ON THE ORBIT

HEIGHT COMPONENT

- THREE-STATION TRACKING -

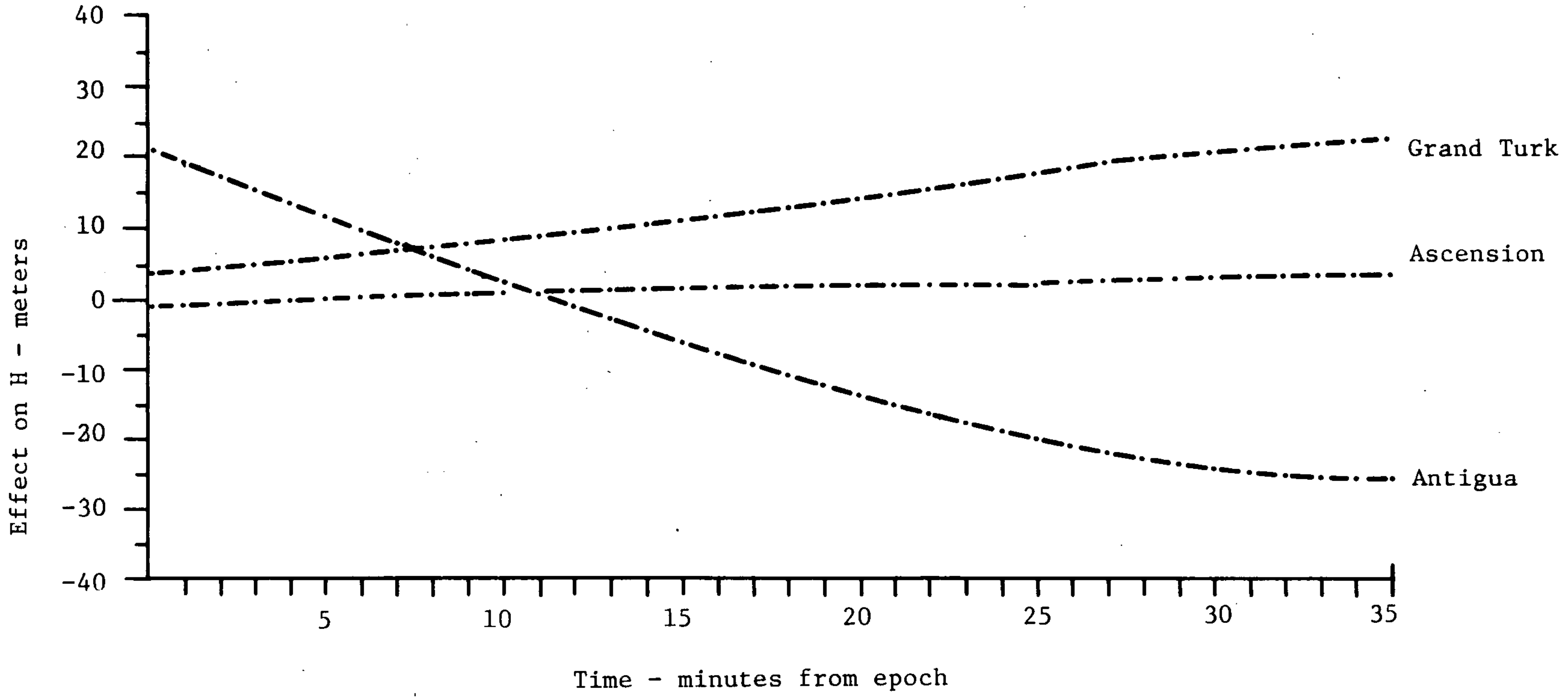


TABLE 1

SUMMARY OF TRENDING ERRORS

			1 MIN. ARC		20 MIN. ARC	
			SINGLE STATION	MULTIPLE STATION ANT - GRT AS8	SINGLE STATION	RANGE SOLUTION MULTIPLE STATION ANT. GRT. AS8
BIAS	RANGE	5 m	1 meter	.5 meters	20 meters	8 meters
	ANGLES	20 sec	.5 meters		8 meters	
SURVEY	X	15 m	1.5 meters	.5 meters	35 meters	10 meters
	Y	15 m	1.5 meters	1.4 meters	35 meters	28 meters
	Z	15 m	1.5 meters	1.7 meters	35 meters	35 meters

NOTE: If the whole problem is solved using one station as a reference, then the X Y Z survey errors can be assumed to be about 5m instead of 15m. This will scale the effects by 1/3.

3.0 CONCLUSIONS

Table 1 is a brief summary of the most salient results obtained from the simulations. Analysis of results leads to several important conclusions and indicate areas where further study is needed. The simulations indicate that:

1. For the tracking configurations studied, there are serious trends in the orbit for profile arcs of 1000 miles or longer. These trends are caused primarily by tracking system errors and station model errors. The trends in the orbit equal or exceed the long wave length profile variations which characterize the dominant features of the geoid. Therefore, other methods or configurations for determining long profile arcs will be required in order for the altimeter to significantly contribute to geoid studies. Profile variations in 100 - 200 mile arcs or less are not seriously masked or distorted by station/tracking system model errors when the altimeter measurements are made during the tracking period. This is true for both the single- and three-station configuration studied.

2. Altimeter calibration must be performed when total H uncertainty and trending are minimized. This occurs at approximately the midpoint of the tracking span for the single-station case. Since there does not appear to be any significant enhancement from three-station tracking, calibrations can best be performed using a single station. The arc length for the calibration should be approximately 1 minute. The pass selected should be a high elevation (80° - 90°) pass over the station so that the altimeter and ground tracking measurement can be compared directly. This will minimize uncertainties caused by sea level and geoid variations. Good sea level data at the station should be available during the calibrations.

3. The use of satellite-to-satellite tracking data to determine the H component of the near earth satellite should be investigated. It is logical to assume that tracking obtained from a near synchronous satellite to the nearer altimeter earth altimeter bearing satellite will provide a better long term determination of H. Since the continuous tracking period will extend over much longer arcs (up to a full revolution in some cases), it may even be possible to maintain a good altimeter reference orbit over entire ocean areas.

4. Additional study of long-arc (one or more revolutions) multiple-station orbit determination should be performed. This study does not consider the use of satellite tracking data from a global distribution of stations for one or more revolutions to obtain reference orbits. It is possible that tracking data from this configuration may provide determination of orbits that have very low radial trends over entire ocean areas.

5. Overall GEOS-C Altimeter utilization planning should be reinvestigated. In addition to considering methods of obtaining ocean profiles, studies are needed to determine how altimeter data, combined with the profile information, can best be used for orbit determination and geopotential coefficient improvements.