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National Aeronautics and
Space Administration

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ABSTRACT

The absolute bias calibration for the GEOS-3 intensive mode altimeter has been measured using two satellite passes whose groundtracks were within 1 km of the Bermuda laser station. The Bermuda laser tracked on the two passes – Rev 4553 on February 25, 1976 and Rev 5471 on April 30, 1976 – and was supported by two other NASA lasers on one pass and by the NASA Spacecraft Tracking and Data Network on the other pass. For each pass, the altimeter data around Bermuda was smoothed and extrapolated to the point closest to overhead at the laser site. This point was used for calibration, eliminating almost entirely the effects of geoid model error on the resulting altimeter bias estimate. After correcting for tide heights and sea state effects, the two passes give calibration biases which are in agreement to within 26 cm and have a weighted mean of -5.69 ± 0.16 m for correcting altimeter measurements to the center-of-mass of the spacecraft (i.e., including the antenna tracking point correction). Since a sea state bias correction has been used in the bias estimation, a different bias is more appropriate for data users not employing a sea state bias correction. For such users, a bias of -5.59 m, appropriate for moderate seas ($H_{1/3} \simeq 2$ m), is recommended.

It was found impossible to reconcile the two calibration passes, as well as a set of altimeter crossovers in the middle of the GEOS-3 calibration area, without allowing for a data time tag

error. On the basis of a selected set of four crossovers, and an assessment of probable sources of timing error, it was concluded that one interpulse period (10.24 msec) should be added to the data time tags. This time tag correction should be used with the above bias value.

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SECTION 1.0

INTRODUCTION

For some applications of the large quantity of altimeter data taken by the GEOS-3 intensive mode altimeter, an absolute calibration of the altitude data is needed. Such applications would include, e.g., determination of the semi-major axis of the ellipsoid best approximating the geoid. This estimation can be made to the accuracy to which (1) the orbit can be positioned relative to the earth's center-of-mass, and (2) the altimeter measurement can be corrected to be a measurement from the spacecraft center-of-mass to the mean sea surface at the nadir point. The computation of accurate center-of-mass orbits requires accurate tracking station positions (particularly height), an accurate value of the geocentric gravitational constant (GM_e), a reasonably large quantity of tracking data, and a good model for the geopotential field. Consequently, orbit determination is a very difficult problem. But it is a problem which is largely separable from an evaluation of the altitude measurement accuracy, for which only orbit accuracy relative to a calibration reference point need be considered.

The validation of the altimeter measurement from the spacecraft to the mean sea surface requires situations in which this distance can be accurately inferred, independent of the altimeter data itself. Effectively, this can be done using satellite passes which are nearly overhead at island laser tracking sites. This technique has the advantage that an accurate a priori knowledge of geoid heights is not required, and is described in Section 3.

One major problem, however, is obtaining satellite groundtracks which are sufficiently close to island tracking stations, along with the necessary supporting tracking data. Particularly was this a problem with a satellite such as GEOS-3, which incorporated no capability for orbit adjustments after orbital insertion. Calibration opportunities were thus dependent upon the groundtrack pattern of the orbit into which the spacecraft happened to be inserted.* There were two island lasers, at Bermuda and Grand Turk, in the GEOS-3 tracking schedule, but near overhead passes were achieved only at Bermuda. Figure 1 shows the groundtracks of GEOS-3 satellite passes in the vicinity of Bermuda. The density of these passes is due basically to chance, since such coverage was not planned and the oceans are by no means uniformly covered with such dense tracking. The Bermuda laser tracked on only two of these passes but, incredibly, the two tracked were the two closest to being direct overhead passes.

One of the two overhead Bermuda passes (Rev 4553) has been previously utilized for altimeter calibration (Martin and Butler, 1977), although without accounting for sea state effects on the altitude measurements and measured tide data on sea surface height. This pass did, however, have tracking by three lasers in the calibration area and should thus have a well determined orbit. The other pass, Rev 5471, had tracking by only 2 calibration area lasers, but the potential still exists for obtaining an accurate height of the spacecraft at the time of Bermuda overflight through the use of S-Band tracking data taken from NASA Spacecraft Tracking and Data Network (STDN) stations on earlier and later passes.

The primary objective of this paper is to obtain a best estimate of the GEOS-3 altimeter calibration bias, using the two available passes and reconciling differences between them. Assuming that orbits with accurate altitudes over Bermuda are obtained, discrepancies between the two passes could be due to one or more of the following:

1. A pass to pass variation in the true altimeter bias.
2. Incorrect time tagging of the altimeter data, resulting in orbit height evaluation at the wrong times.
3. Errors in calibration on one or both passes due to improperly modeled tides or sea state effects.

*The GEOS-3 spacecraft was indeed inserted into the planned nominal orbit, and frequent repetition of groundtrack was not intended. The planned calibration technique was based on the use of a gravimetric geoid model and calibration passes in the middle of the complement of laser tracking sites.

The pass to pass bias variation is effectively ruled out on the basis of the altimeter design and the lack of any evidence for instrument drift from on-board calibration data taken during the GEOS-3 mission. Timing problems, however, cannot be ruled out. During the initial processing of GEOS-3 altimeter data, there were problems with time tagging from at least two sources.* Based on this history, and the fact that crossover differences show strong evidence of timing problems, timing calibration will be considered in this paper along with height calibration. It is recognized that pass to pass calibration differences will exist due to errors in accounting for tides and sea state effects. But analysis of such errors indicates that they are not sufficient to account for observed pass to pass variations, thus adding further weight to the timing error explanation for pass to pass variations.

To assist in the resolution of the timing question, additional GEOS-3 passes through the calibration area have been selected. The utility of such passes for timing bias evaluation depends upon accurate orbits and the ability to predict sea surface height variations between the times of crossover passes. Four pairs of crossovers best satisfying these criteria are selected and analyzed in Section 4 to determine the existence of and a best estimate for a timing error. The results from this analysis are then applied in Section 5 to estimate the altimeter height bias.

Since GEOS-3 data has been distributed by NASA Wallops Flight Center at various times since the spacecraft launch in April, 1975, the terms "height bias" and "timing bias" used in this report should be clarified. For all data distributed to official GEOS-3 investigators prior to 1 January 1980, no height bias was applied to any data. In the calibration report by Martin and Butler (1977), it was concluded that the height bias was −5.3 m, including the spacecraft center-of-mass offset. This number was based on the Rev 4553 Bermuda overflight and included a theoretically computed time tag correction of −11.559 msec for the cumulative altitudes used in

*Errors included −20.8 msec due to a verified STDN GEOS-3 time correlation error and 10.24 msec due to an error in the altimeter lag calculation (Martin and Butler, 1977).

the analysis. For the GEOS-3 altimeter data distributed after 1 January 1980 (essentially the entire ~4 year data set), this time tag correction has been applied, and a height bias of -5.3m has also been applied to computed sea surface heights. The biases referred to in this document are to a height bias that is a replacement for the -5.3m, and a timing bias that is a correction to the "corrected" time tags.

SECTION 2.0

ORBIT ESTIMATION FOR BIAS CALIBRATION

The groundtracks for Revs 4553 and 5471 are shown in Figure 2, with segments indicated for each pass for which the altimeter footprint (~3.5km in diameter) contained some land. These data segments are not used in the calibration process. Since the groundtrack passes about 1km away from the laser site, the Rev 5471 calibration requires a geoid correction. However, this correction can be quite accurately obtained from the smoothed and extrapolated Rev 4553 data.

2.1 REV 4553 ORBIT ESTIMATION

There was tracking by 3 NASA calibration area lasers on Rev 4553, and this data set was used for obtaining the definitive orbit over Bermuda. The laser station positions used were those obtained by Krabill and Martin (1978), listed in Table 1. These positions were chosen as being the best available center-of-mass coordinates, based on accuracy of baselines between stations. The data fits on this single pass solution are listed in Table 2 and show RSS's at approximately the data noise level. Table 2 also shows that there was not much data, particularly from the Goddard laser (STALAS). However, assuming the data points taken to be valid, there is a sufficient quantity and distribution of data to determine the orbit over Bermuda.

For Rev 5471, there is laser tracking by only the Bermuda laser and the Patrick AFB laser. Tracking by the latter station does not commence until the elevation angle from the Bermuda laser is down to almost 35°, so these 2 lasers cannot by themselves adequately estimate the satellite altitude as it passes over Bermuda. Accordingly, a technique was investigated of using S-Band

and laser tracking data from passes before and after the pass of interest, along with the single Bermuda laser pass. Since the satellite altitude at the time of Bermuda passage was available for Rev 4553 from the 3 laser solution, the multiple revolution solution was tested on Rev 4553. S-Band and laser positions determined by Marsh, et. al., (1977), listed in Table 3, were used for these solutions. Table 4 shows estimates of the satellite altitude error over Bermuda from multi-revolution S-Band/laser solutions, with the single pass laser arc used as a reference. For both S-Band/laser orbits, only the single Bermuda laser pass is used in the orbital solution and the laser data is in approximately the middle of the arc.

Table 4 shows that, using the single pass 3 laser arc as a reference, the 3 revolution S-Band/laser solution has a 19 cm altitude error over Bermuda, compared to only a 3 cm error for the one day arc. This difference has been tentatively attributed to a geometric imbalance of laser tracking from Bermuda, since there are 30 data points prior to PCA, and only 3 data points after PCA. However, it could also be due to the limited amount of S-Band tracking during the 3 revolution arc. Table 4 does demonstrate, however, that a multi-revolution solution using S-Band range rate data and the single high elevation pass of laser data can indeed produce an orbital altitude at PCA on the laser pass which is accurate at the few (~2-3) cm level. Thus, the multi-revolution solution can be used with confidence for the Bermuda pass on Rev 5471 for which 3 laser tracking is not available.

2.2 REV 5471 ORBIT ESTIMATION

Both 3 revolution and 1 day arcs using S-Band data and the Rev 5471 Bermuda laser pass were reduced and the orbit heights at Bermuda PCA compared. The difference, shown in Table 5, is only 2 cm. Compared to Rev 4553, this small difference can be attributed to some combination of a better geometrical distribution of laser data and more S-Band tracking. It also indicates that either orbit may be used with confidence for analysis of the altimeter data on Rev 5471. Because it should be less affected by geopotential model errors, the 3 revolution solution was selected.

SECTION 3.0

BIAS CALIBRATION TECHNIQUE

As discussed in the previous section, accurate satellite heights over Bermuda – relative to the laser site – are available on GEOS-3 Revs 4553 and 5471. To use these passes for altimeter bias calibration, it is necessary to deduce the measurements that the altimeter would have made had it been able to make measurements to the geoid surface as it passed over the laser tracking station. Lacking a detailed geoid model of the desired accuracy around Bermuda, the adopted procedure involves the following basic steps:

1. Correct the altimeter data for propagation, sea state and off-nadir effects, with all data deleted for which there was any land in the altimeter footprint. This deletes 1–1.5 seconds of data for each of the two passes of interest.

2. Smooth the remaining over-water data and extrapolate across the island to obtain the measurement at the time of closest approach to the tracking station. Differencing this measurement from the calculated orbit altitude above the tracking station then gives the altimeter bias, assuming the over-water mean sea surface to have been equivalent to mean sea level.

3. Correct the calibrations for sea surface deviations at the time of each pass from mean sea level. This includes not only ocean tides but non-tidal effects as well. Tide gauges – properly located and properly operating – can satisfy this need. To first order, at least, effects such as ocean loading and earth tides cancel out, since the ocean surface and station height are approximately equally affected.

Figure 3 shows graphically the various components in the overhead calibration, with the altimeter measurement, h_{alt}, assumed to be corrected as indicated in 1 above. In practice, station positions and sea surface height calculations are made relative to a reference ellipsoid. Directly over the tracking site, the two geoid heights are identical, so any errors cancel out in the calibration bias estimation.

The application of the above 3 steps in overhead calibration to Revs 4553 and 5471 will now be discussed, including problems due to questionable data or correction techniques.

3.1 DATA CORRECTIONS

The altimeter measurements are affected by propagation through the atmosphere, and by distortion of the return pulse from the ocean surface from its "nominal" shape. The return pulse shape will be distorted by either a non-zero off-nadir angle of the altimeter antenna on-board the spacecraft, or by the sea surface if it is anything other than the normal rough sea. In practice, the latter can be a problem both for high sea states and for very calm seas.

Propagation corrections for altimeter data were made using the Saastomoinen (1972) formula

$$\Delta H \text{(meters)} = 0.002277 \left[p + \left(\frac{1255}{T} + 0.05\right) e\right] \qquad (1)$$

where

- p is the ground level total barometric pressure in millibars
- T is the ground level temperature in °K
- e is the ground level partial pressure of water vapor in millibars

For both of the passes of interest, pressure, temperature and relative humidity were recorded at Bermuda at the time of the pass. Table 6 lists the meteorological data and the computed corrections. Conservatively, the refraction correction computed using the above formula and measured data would be expected to be accurate to within 2% (Goad and Martin, 1977). Since the correction itself is ~2.4 m, the uncertainty in the correction would then be less than 5 cm.

Both calibration passes are daytime passes, occuring at ~3 P.M. local time on Rev 4553 and ~1 P.M. local time on Rev 5471. Ionospheric effects, based on the Bent Model (Schmid et. al., 1973), are approximately 5 cm for each pass. This correction is included, although it is well below the accuracy level of the resulting calibration.

Sea state effects on altimeter height measurements fall into two categories -- an instrument effect and an EM bias effect – which may be treated independently. The instrument correction is due to pulse shape distortions caused by different sea states and is normally considered along with off-nadir angle pointing, which also causes pulse shape distortion. Theoretical curves for the instrument bias effects of various sea states have been prepared as functions of off-nadir angle, and are given in the GEOS-3 Altimeter Ground Truth Document (Wallops Flight Center, 1975). For all situations except very high sea states and off-nadir angles well beyond the $\sim 0.5^\circ$ GEOS-3 spacecraft nominal stabilization, the instrument bias effects are at the few centimeter level and can, for all practical purposes, be neglected.

EM bias effects arise due to a non-symmetric distribution of surface electromagnetic backscatter cross-section about the true instantaneous mean sea surface, with wave troughs tending to scatter more strongly than wave crests. EM bias (sometimes referred to simply as sea state bias when the instrument effect is also included) has been approached in several different ways. On the basis of comparisons of altitude measurements from high sea state passes with overlapping passes with low sea states, Miller and Priester (1978) have developed an empirical curve, shown in Figure 4, for the effects of sea state on the GEOS-3 altimeter bias. For the lower wave heights, this curve is nearly linear and shows general agreement with the results of measurements by Yaplee et. al., (1971) from a tower located off the coast near Norfolk, Virginia. Yaplee's results showed a bias towards the wave troughs which was related to the wave height by

$$\Delta b\,(\mathrm{cm}) = 8.4\,H_{1/3}(\mathrm{m}) - 4.6 \qquad (1a)$$

This relation gives a zero effect of sea state from a significant wave height of 0.55m, whereas the reference wave height for the curve in Figure 4 from Miller and Priester's report appears to be at the 1-3m level. The EM bias subject has also been approached theoretically by Jackson (1979), with the resulting approximate formula

$$\Delta b\,(\mathrm{cm}) = 5.0\,H_{1/3}(\mathrm{m}) \qquad (1b)$$

Strictly speaking, Jackson's expression should allow for the dependence of EM bias with height skewness, but this refinement would be well beyond the current stage of experimental validation and also beyond our needs. Equation (1b) will be used for sea state bias corrections, although the differences between this Equation, Equation (1a), and the curve in Figure 4 are considerably below the uncertainty in each.

Extensive effort has been devoted to the estimation of sea state using GEOS-3 altimeter waveform data, so that the data on the passes of interest can be used to estimate the sea state around the times of Bermuda passage. This has been done by Roy (1979) for Revs 4553 and 5471, with the results shown in Table 7. Also shown are the altitude bias corrections based on Equation (1b). Rev 5471 occurred during low sea state conditions, such as occurred for the vast majority of GEOS-3 passes, and the reference for the Figure 4 curve.

The interpretation on the sign of the sea state bias is that high sea states cause larger altitude measurements. The correction for Rev 4553 is too large to neglect if the results are to be applicable to altimeter data passes taken under low sea state conditions. The sea state bias correction for Rev 5471 is included only for consistency.

3.2 DATA SMOOTHING

Smoothing of the altimeter data, with extrapolation across Bermuda, was performed using the ALTKAL program, which was developed expressly for the optimum linear filtering of GEOS-3 altimeter data (Fang and Amann, 1977). This program is a combined forward and backward Kalman filter and extrapolates across missing or edited data points. The filter is based on the third order Markov model for geoidal undulations given by Jordan (1972). The particular ALTKAL version used first removes a pass mean and then employs an iteration feature with filter parameters changed between iterations. Although some previous results (Martin and Butler, 1977) have been based upon the prior removal of the Marsh-Chang 5′ x 5′ geoid, (Marsh and Chang, 1977), no geoid was removed for the results reported here. Parameters chosen for filtering were:

Geoid Undulations	– 2m amplitude 50km correlation length	first iteration
	20cm amplitude 25km correction length	second iteration
Altimeter Noise	– 60cm white noise at 10/sec data rate	

The raw and smoothed altimeter residuals after orbit removal are shown in Figures 5 and 6 for Revs 4553 and 5471, respectively. Segments of edited data due to land in the altimeter footprint are indicated. The smooth curve includes extrapolated results at the times of edited data.

3.3 TIDE AND SEA SURFACE HEIGHT CORRECTIONS

As indicated above, corrections can be made for tides and non-periodic fluctuations in sea surface height through the use of an appropriately placed and satisfactorily operating tide gauge. As shown in Figure 2, there is a tide gauge in St. Georges Harbor at Bermuda, less than 4 km from the laser site. Since the harbor is open on two sides, discrepancies between the tide gauge measurements and open ocean tides in the area would normally be expected to be only at the few centimeter level. On the other hand, high winds could give significantly erroneous tidal values if they were persistent and in the right direction. But the tide gauge data is still the best sea surface height data available, assuming that the gauge is properly operating.

Figures 7 and 8 show the tide gauge data (Rutstein, 1977) for an approximately one day period around the times of Bermuda crossing on Revs 4553 and 5471. For Rev 5471, the tides recorded seem quite normal and, indeed, are within a few centimeters of predictions (NOAA, 1975). For February 25, however, the period around Rev 4553 shows anomalous behavior as compared to the predicted cycle. In fact, the data suggests that the tide gauge was clogged from approximately 18^h on February 25 to between 8^h and 9^h on February 26.* From the possible choices of accepting the tide gauge data, using the predicted tide or discarding the pass altogether, it was decided to use the predicted tide for the following reasons:

1. The tide gauge closely followed the predicted tide up until approximately one hour prior to the GEOS-3 pass crossing of Bermuda.

*The tide gauge records did indeed have a record of clogging (Rutstein, 1977) on February 24, but not on February 25. However, the recorded data on February 24 does not show anomalous behavior, such as occurred on February 25.

2. It is not believed that the $H_{1/3}$ seas of 4m and the associated winds of ~13 knots (deduced from the GEOS-3 waveform data) are sufficiently large to induce the observed tide gauge behavior, particularly for open seas.

3. The observed tide gauge pattern very closely resembles what would be expected from a clogged tide gauge.

From Figure 7 we read a value of 5cm as the tide height at the time of the GEOS-3 crossing (~$19^h 15^m$) which, compared to the 12cm prediction by the Mofjeld (1975) tide model, means that a -7cm tide correction is to be applied to the data as normally processed using the Mofjeld tide.

SECTION 4.0

TIMING BIAS ESTIMATION

In this section, it is considered that the GEOS-3 data may be inappropriately time tagged, and laser supported crossing passes in the calibration area, other than the two calibration passes, are selected to supply independent timing bias estimates. The orbit heights for such passes should be almost as accurate as the Bermuda overhead passes. The crossovers suffer primarily from non-tidal temporal sea surface height changes between passes, plus anything unusual happening on particular passes.

Because of orbit eccentricity and earth oblateness, GEOS-3 altitude rates on North-South and South-North passes through the calibration area differ by some 30-50m/sec. Any error in data time tagging would thus result in sea surface height differences at crossovers, even if the altimeter were perfectly stable, and there were no errors in orbits, propagation corrections, tides or other temporal sea surface height effects. To first order, the crossover differences are equal to the product of the timing error and the differences in altitude rates on the crossing passes. For a 50m/sec rate difference, a 5cm crossover difference would result for each msec of timing error.

There were some 20 passes of GEOS-3 through the calibration area for which both altimeter data was taken and for which at least 3 laser tracking stations collected data. Although crossovers for all these passes are potentially usable from an orbit accuracy standpoint, eddies are known to exist in at least the northern portion of the calibration area. Such eddies have diameters on the order of 100–200km and topographic variations on the boundaries of 50–100cm. The movement of an eddy boundary through the crossover region between passes would lead to a crossover height difference which would severly distort the results obtained from a limited number of passes. To avoid such potential problems, as well as to minimize other temporal sea surface height effects, a set of crossovers were selected having the following characteristics:

1. The two passes in a crossover pair occur less than 24 hours apart.
2. Each pass is tracked by at least 3 lasers.

There are a total of 4 such passes, as shown in Figure 9. In addition, the Rev 4553-5471 crossover is included to observe its consistency after timing bias adjustment. Table 8 shows a tabulation of the crossover differences from Figure 9, along with the altitude rate differences and sea state corrections.

For small timing errors, the crossover differences are linearly related to the timing errors by

$$\Delta H_i = \Delta\dot{H}_i \Delta t + \sigma_i \qquad (2)$$

where

ΔH_i is the height difference at the i^{th} crossover point

$\Delta\dot{H}_i$ is the altitude rate difference at the i^{th} crossover point

σ_i is the uncertainty of ΔH_i due to measurement noise and various other error sources.

After smoothing, the effects of measurement noise are approximately 12cm on the at sea passes. Other errors should be considerably smaller and would not contribute significantly to the RSS error. The crossover difference uncertainties will be the combined uncertainties for the intersecting passes, or $12\sqrt{2}$cm, assuming the pass to pass errors to be independent. The weighted least squares solution for Δt from Equation (1) is

$$\Delta\hat{t} = (\Sigma\Delta\dot{H}_i\Delta H_i/\sigma_i^2)/\Sigma(1/\sigma_i)^2 \qquad (3)$$

Substituting for the ΔH's and $\Delta\dot{H}$'s from Table 8 results in an estimated timing bias of 11.46 ± 2.2 msec, with the sigma of 2.2 msec based on the 17 cm crossover sigma.

Numerous checks have been made of the GEOS-3 altimeter timing diagrams, and their accuracy has been rechecked with the altimeter builder. No explanation for a timing error on the order of 11 msec has been found. Nevertheless, a timing error of 10.24 msec is adopted. This value is well within 1σ of the estimated timing bias and is exactly one interpulse period (time between altimeter transmitted pulses). The closeness of the estimated timing bias to an interpulse period strongly suggests that

1. The timing diagrams have not been properly interpreted, or
2. The altimeter was not built consistent with the timing diagrams.

Regardless of which, if either, of these explanations is correct, the application of the timing correction produces more consistent data at intersections. For the four at sea intersections given in Table 8, the RSS drops from 47 cm to 14 cm with the use of the adopted Δt. And without a timing bias, the two height calibration passes, Revs 4553 and 5471, are virtually impossible to reconcile. Accordingly, the timing bias is considered an integral part of the calibration.

SECTION 5.0

CALIBRATION RESULTS

The overhead calibration technique depends crucially upon obtaining the altimeter measurement which would be made directly over the tracking station, as if the altimeter were tracking to the normal ocean surface. The procedure for doing this is to smooth the data taken totally over water, and extrapolate to the point over the tracking station. The smoothing technique used has been discussed in Section 3.

The smoothed residuals for Revs 4553 and 5471 are shown in Figures 5 and 6. To deduce the altimeter bias from these residuals, we must consider the algorithm actually used for residual computation and what corrections or additions should be made to it. From the overhead calibration geometry shown in Figure 3, the residual at the overhead point is the difference between the satellite distance to the ellipsoid based on the altimeter data plus appropriate tide and geoid models, and the satellite distance to the ellipsoid based on the tracking data and the station height above the ellipsoid. Neglecting the bias, the residual is expressed from Figure 3 as

$$\begin{aligned} \text{Residual} = h_{alt} + \left\{\delta h + h_{tide}\right\} + h_{geoid}\,(\text{Alt}) \\ - R - h_{MSL} - h_{geoid}\,(\text{Sta}) \end{aligned} \tag{4}$$

where

h_{alt} is the smoothed (and extrapolated) altimeter measurement corrected for propagation and sea state effects.

δh is the non–tidal deviation of the sea surface height from mean sea level. In the residual computation, this term is included with the measured tide when tide gauge data is used.

h_{tide} is the tide height based on a tide gauge or tide gauge predictions.

h_{geoid} (Alt) is the height of the geoid above the ellipsoid used in computing the ellipsoidal height based on the altimeter data. This geoid was neglected in computing the altimeter residuals shown in Figures 5 and 6.

R is the satellite height above the tracking station, as deduced from the tracking data.

h_{MSL} is the tracking station height above mean sea level as determined by local survey.

h_{geoid} (Sta) is the geoid height used for the tracking station (= station height above ellipsoid – height above mean sea level).

Additional corrections that should be applied are:

- Correct h_{alt} for ionospheric propagation
- Correct h_{alt} for sea state effects
- Substitute the measured tide gauge height for the tide model value (automatically including δh)

Table 8 summarizes these corrections for the two Bermuda near overhead flights. For Rev 5471, an additional geoid correction has been included, since the groundtrack has a 1 km offset from the tracking station and Rev 4553 indicates that there is approximately a 15 cm variation in the geoid over this distance. The Rev 4553 groundtrack passes sufficiently close to the tracking station that no correction is needed.

Also included in Table 8 are nominal estimates of errors in the residual corrections tabulated, plus estimated effects in the residuals due to measurement noise, tropospheric refraction correction errors, and orbit height errors. The dominant error source is measurement noise. Assuming that the computed 1σ uncertainties for the two passes are independent, as would be expected based on the error sources, a single bias can be estimated by combining the results of the two passes. The result is a best estimate of the altimeter bias of -5.69 ± 0.16 m.

SECTION 6.0
SUMMARY AND CONCLUSIONS

One South-North pass (Rev 4553) and one North-South pass (Rev 5471), each passing across Bermuda and having tracking support by the Bermuda laser, have been analyzed to estimate the height bias for the GEOS-3 altimeter. The bias estimate, based on an optimum combination of data from the two passes, was:

$$b = -5.69 \pm 0.16\text{m} \qquad (5)$$

The crossover difference between the two passes was 26 cm after allowing for a 10.24 msec timing error.

Sea surface height corrections were made for Rev 5471 based on measured tide gauge data. For 4553, sea surface height corrections were based on predicted tide gauge measurements after concluding that the tide gauge was clogged at the time of the pass. Up until the time of the apparent clogging, approximately one hour prior to the pass, the measured tide and predicted tide were in close agreement. Thus, unless very anomalous conditions arose during the hour prior to the pass, the predicted tide should be accurate.

The above bias was also estimated using a sea state bias correction of 5% of significant wave height, and is thus an appropriate value for zero sea state. Although there is presently some question as to the details of the sea state bias correction, it is considered that a correction of approximately the magnitude used is essential in the interpretation of observed altimeter data. For altimeter data users not making a sea state bias correction, the use of a bias value for a nominal sea state (e.g., $H_{1/3} \simeq 2\,m$) is recommended, thus leading to a modified bias of

$$b' = -5.59\,m \; (H_{1/3} = 2\,m) \qquad (6)$$

A timing bias was estimated using 4 crossovers within the calibration area which were supported by tracking from 3 laser sites. The two passes in each crossover pair occurred within 8 revolutions, so that temporal sea state changes due to eddy movements, etc. were minimized. Sea state bias corrections were added and a timing bias of 11.46 msec was estimated. Considering the closeness of this value to one altimeter interpulse period (10.24 msec) and the probable origins of a timing error, a timing error of one interpulse period was adopted, or

$$\Delta t = 10.24\,\text{msec} \qquad (7)$$

Although it has not been possible to verify some physical explanation for such an error, the evidence from crossover differences is considered overwhelming and it is recommended that the above Δt be added to GEOS-3 altimeter time tags before using the data.

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Table 1
NASA Laser Tracking Station Coordinates
(Krabill, et. al., 1978)

Station		Geodetic Latitude*			E. Longitude			Height* (Meters)
Name	Number	DEG	MN	SECONDS	DEG	MN	SECONDS	
STALAS	7063	39	1	13.3843	283	10	19.7510	14.959
BDALAS	7067	32	21	13.8003	295	20	37.8985	-26.526
GRTLAS	7068	21	27	37.8189	288	52	4.9867	-22.096

*Ellipsoidal parameters: a_e = 6378145m, 1/f = 298.255.

Table 2
Laser Tracking Support on GEOS-3 Rev 4553,
February 25, 1976

Station	Start of Track		End of Track		Max. El.	Total Number of Points	Number of Wtd. Points	RSS of Wtd. Pts.
	Time	Elevation	Time	Elevation				
Grand Turk (GRTLAS)	$19^h\ 12^m\ 06^s$	23°	$19^h\ 16^m\ 07^s$	20°	28°	146	145	4.88 cm
Bermuda* (BDALAS)	$19^h\ 13^m\ 04^s$	37°	$19^h\ 15^m\ 51^s$	74°	74°	30	30	4.54 cm
	$19^h\ 16^m\ 54^s$	48°	$19^h\ 17^m\ 02^s$	46°	46°	3	3	4.04 cm
Goddard (STALAS)	$19^h\ 18^m\ 17^s$	58°	$19^h\ 18^m\ 24^s$	58°	58°	2	2	0.498 cm
Totals						184	180	4.96 cm

*Data segments before and after ~1 minute data gap are summarized separately.

Table 3
S-Band/Laser Tracking Station Coordinates
(Marsh, et. al., 1977)

Station		Geodetic Latitude*			E. Longitude			Height* (Meters)
Name	Number	DEG	MN	SECONDS	DEG	MN	SECONDS	
BDATKS	0002	32	21	4.533	295	20	31.325	–30.100
MI23	0041	28	30	27.306	279	18	23.444	–41.000
ORRTKS	0037	–35	37	40.4110	148	57	25.1690	943.390
ROSRAN	0031	35	11	45.4340	277	7	26.5310	822.340
ULASKR	0018	64	58	19.2330	212	29	13.2350	333.910
QUITKS	0006	–00	37	18.9670	281	25	10.4040	3578.860
BDALAS	7067	32	21	13.7672	295	20	37.8902	–36.869

*Ellipsoidal parameters: a_e = 6378155m, 1/f = 298.255.

Table 4
Comparison of GEOS-3 Rev 4553 Orbit Heights Over Bermuda From Multi-Revolution Data Arcs With Definitive Single Pass Laser Solution

Orbit 1 Data Set	Orbit 2 Data Set	Orbit 1 – Orbit 2 Height Differences at Time of Bermuda Laser Crossing (19^h 15^m 19.6^s on 2/25/76)*
3 Rev S-Band Range Rate Data on Revs 4552-4554, plus Bermuda laser data on Rev 4553.	Laser data from Bermuda, Grand Turk and Goddard on Rev 4553.	-19 cm
1 day S-Band Range Rate Data (7^h 50^m on 2/24 to 11^h 15^m on 2/26) plus Bermuda laser data on Rev 4553.	Laser data from Bermuda, Grand Turk and Goddard on Rev 4553.	-3 cm

*After correction for 34 cm difference between Bermuda heights used for Orbit 1 and Orbit 2.

Table 5
Comparison of GEOS-3 Rev 5471 Orbit Heights Over Bermuda as Determined From Multi-Revolution Arcs of Different Lengths

Orbit 1 Data Set	Orbit 2 Data Set	Orbit 1 – Orbit 2 Height Differences at Time of Bermuda Laser Crossing (17^h 3^m 40.3^s on 4/30/76)
3 Rev S-Band Range Rate Data on Revs 5470-5472, plus Bermuda laser data on Rev 5471	1 day S-Band Range Rate Data (3^h 11^m on 4/30 to 6^h on 5/1) plus Bermuda Laser Data on Rev 5471	-2 cm

Table 6
Bermuda Meteorological Data and
Tropospheric Propagation Corrections
for Calibration Passes

Rev No.	Pressure	Temperature	Relative Humidity	Tropospheric Correction
4553	1030 mb	293°K	45%	2.45 m
5471	1021 mb	293°K	35%	2.40 m

Table 7
Approximate Sea State Biases for the
Two GEOS-3 Calibration Passes

Rev No.	Wave Height ($H_{1/3}$)	Sea State Bias (Eqn. 1h)
4553	~4 m	20 cm
5471	~1 m	5 cm

Table 8
Data Used for Timing Bias Estimation

Revolution Pair	Rate Difference	Sea State $H_{1/3}$	Crossover Difference	Sea State Correction	Corrected Crossover Difference	Crossover Difference with Adopted Δt Applied
1. 1718-1710	−29.6m/sec	2.6m/1.7m	−.08m	−.05m	−.13m	.17m
2. 2102-2094	−31.4	1.1m/2.4m	−.37m	+.07m	−.30m	.02m
3. 4476-4482	−46.17	3.8m/2.5m	−.58m	−.07m	−.65m	−.18m
4. 4604-4610	−45.84	1.45m/.6m	−.54m	−.04m	−.58m	−.11m
5. 5471-4553	−49.78	1m/4m	−.92m	+.15m	−.77m	−.26m

Estimated Timing Biases

$\Delta t = 11.46$ msec ± 2.2 msec (Pairs 1-4)

Adopted Timing Bias

$\Delta t = 10.24$ msec

Table 9
Computation of GEOS-3 Altimeter Bias Estimates
Using Two Bermuda Overflights

	Rev 4553	Rev 5471
Measurement Residual at closest point to laser	35.08 ± .20m*	34.19 ± .20m*
+ Geoid height used for Bermuda laser	-39.97m	-39.97m
+ Tropospheric propagation correction	-.05 ± .03m	0 ± .03m
+ Ionospheric propagation correction	-0.05 ± .02m	-0.05 ± .02m
+ Tide correction Tide gauge-Mofjeld model for Rev 5471 Tide prediction-Mofjeld model for Rev 4553	-0.07 ± .10m	-0.0 ± .03m
+ Sea state bias correction (5% of $H_{1/3}$)	-.20 ± .10m	-.05 ± .03m
+ Geoid correction from closest point to Laser Site - based on Rev 4553 observed slope	0.0 ± 0.0	-.15 ± .03m
+ Orbit height correction	0.0 ± .03m	0.0 ± .03m
+ Timing bias correction (+.01024 seconds)	-0.28m	0.23m
Estimated Pass Bias	-5.54 ± .25m	-5.80 ± 0.21m
Weighted Mean Bias	-5.69 ± 0.16m	

*Uncertainty due to measurement noise.

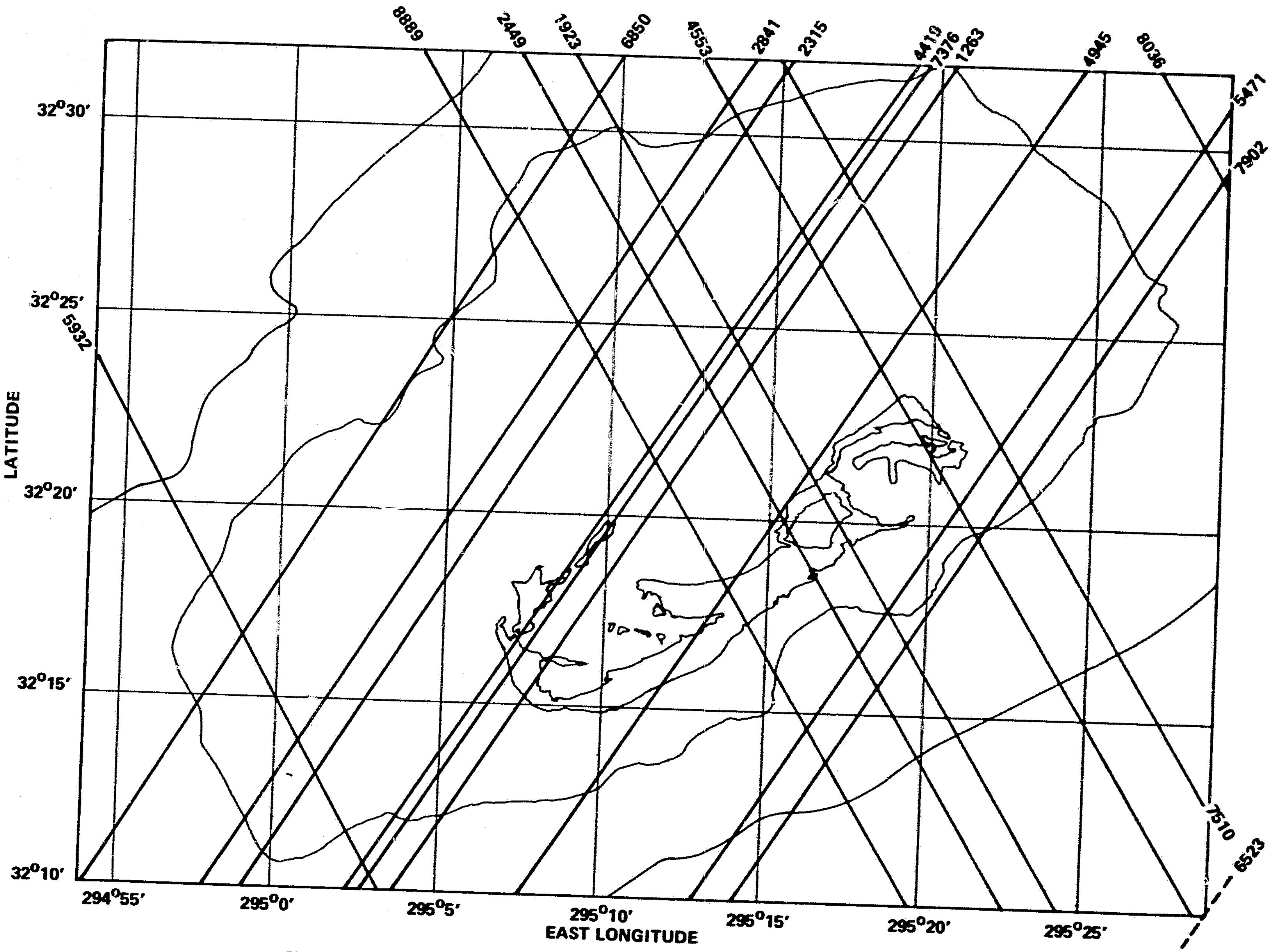

Figure 1. Groundtracks for 17 GEOS-3 Passes Across or Near Bermuda

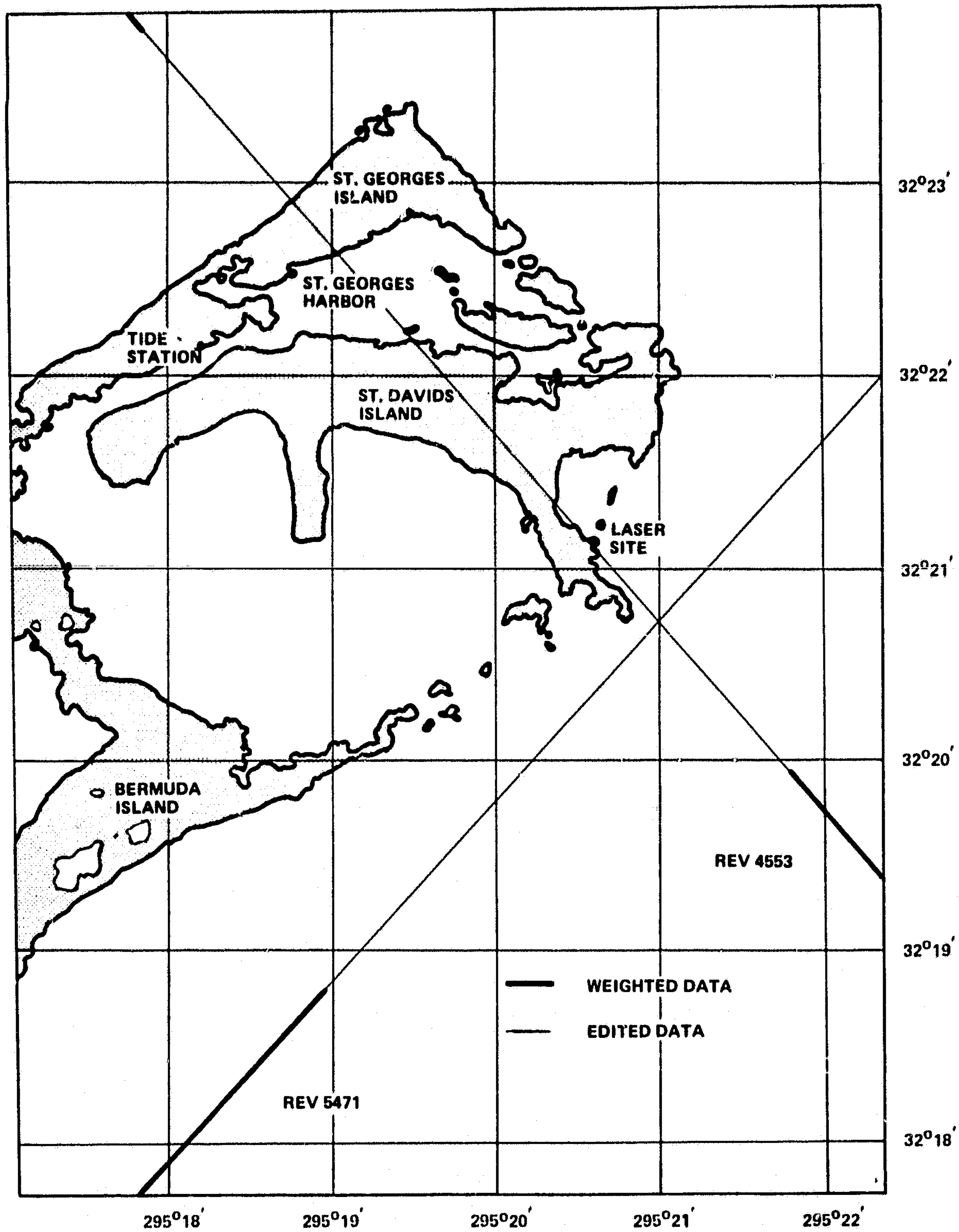

Figure 2. Groundtracks of GEOS-3 Altimeter Calibration Passes

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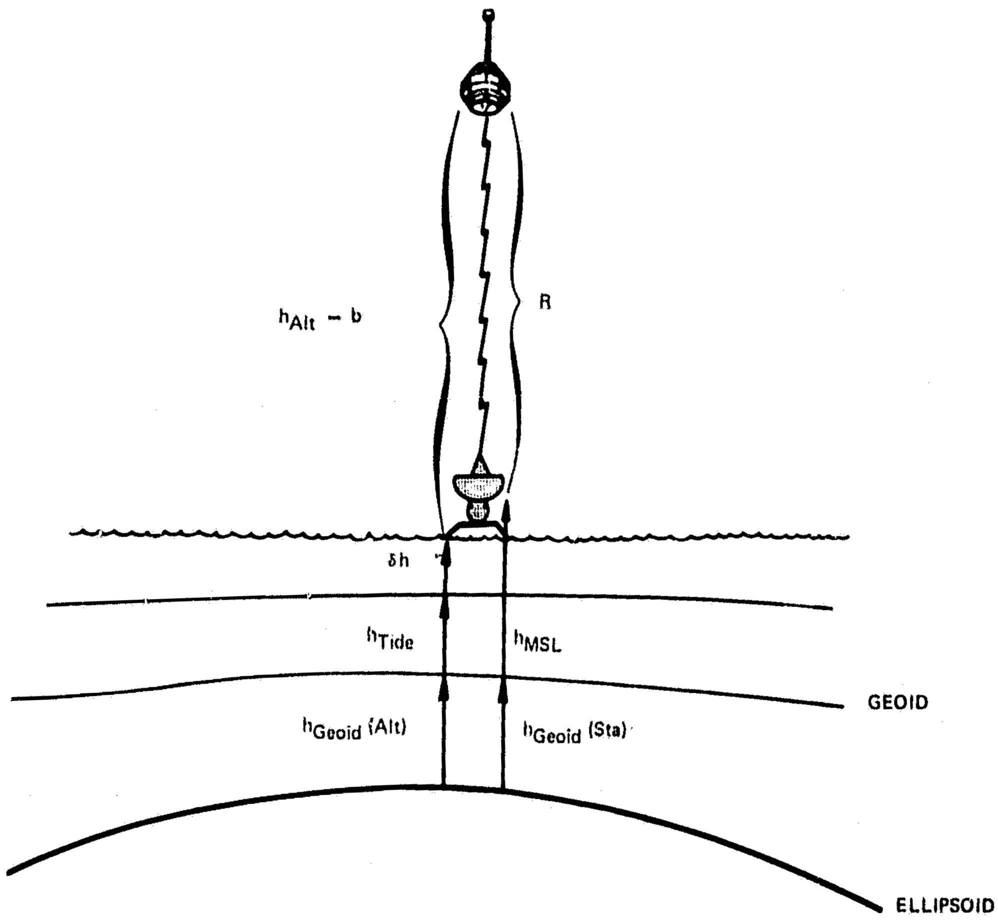

Figure 3. Calibration Geometry Using Overhead Pass

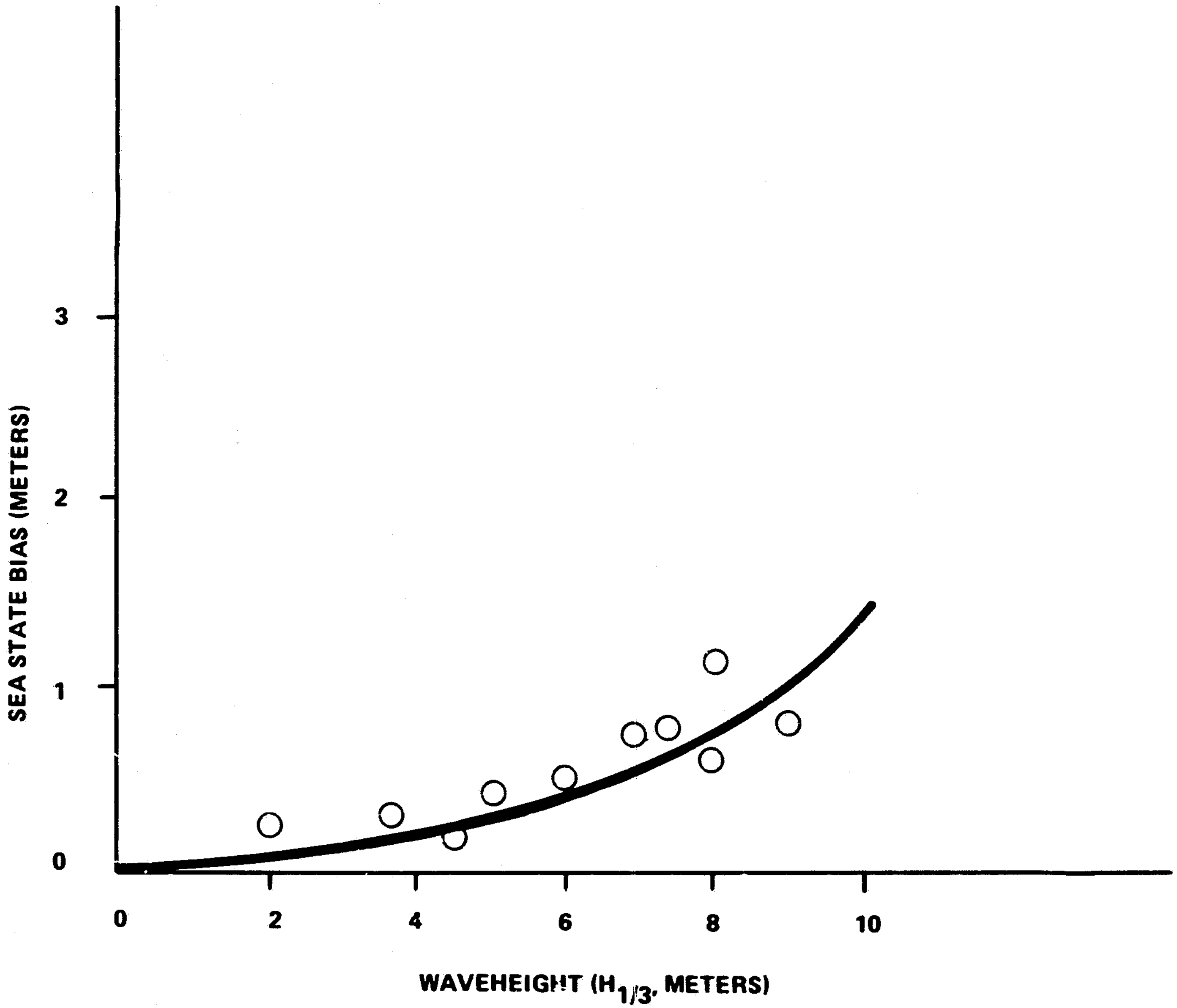

Figure 4. Observed GEOS-3 Altimeter Bias Due to Sea State Effects. Results Obtained by Miller and Priester (1978) from Data Taken on GEOS-3 Revs 4846, 3288, 2216, 1633, 6893

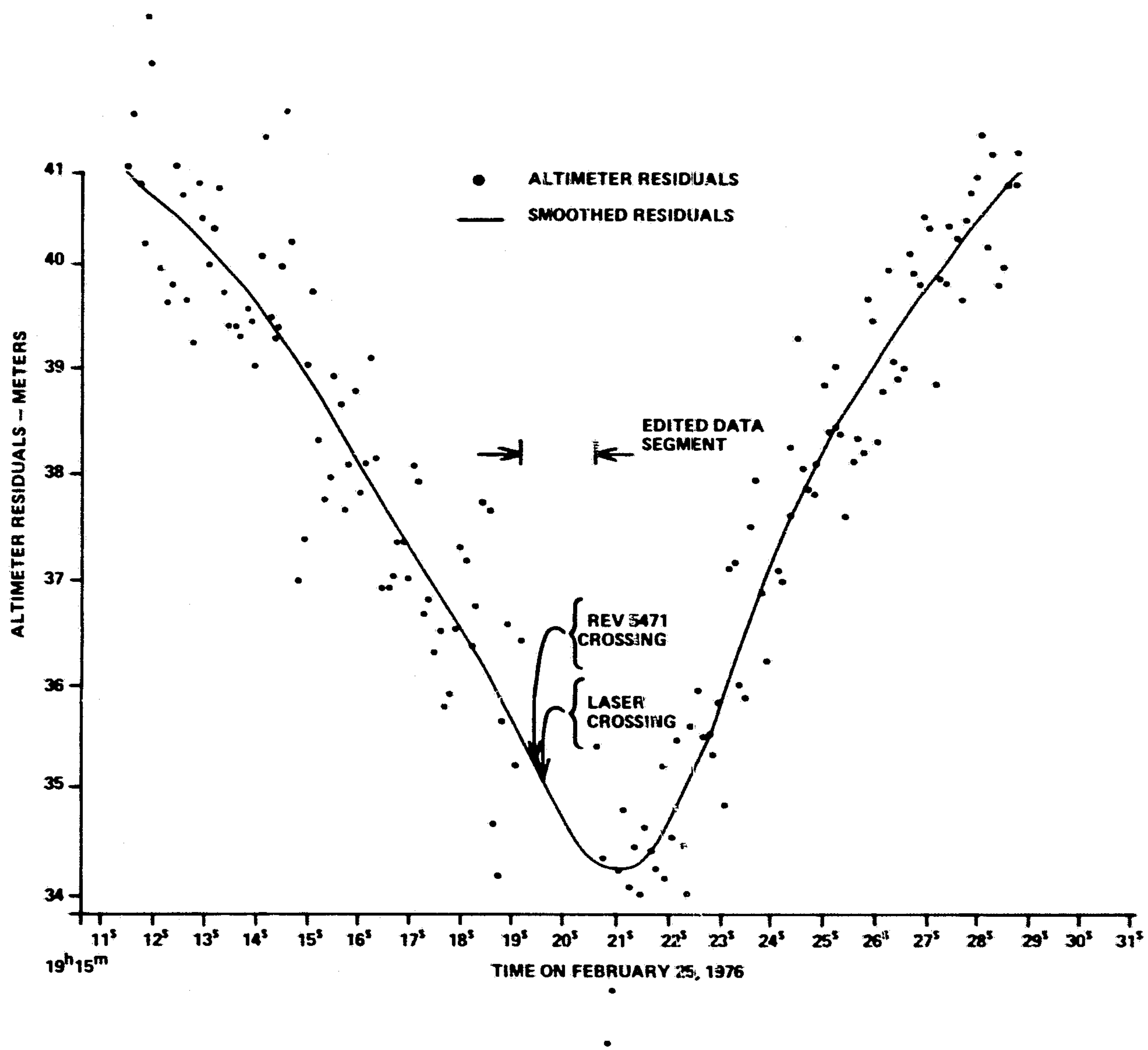

Figure 5. Altimeter Residuals Across Bermuda on GEOS-3 Rev 4553

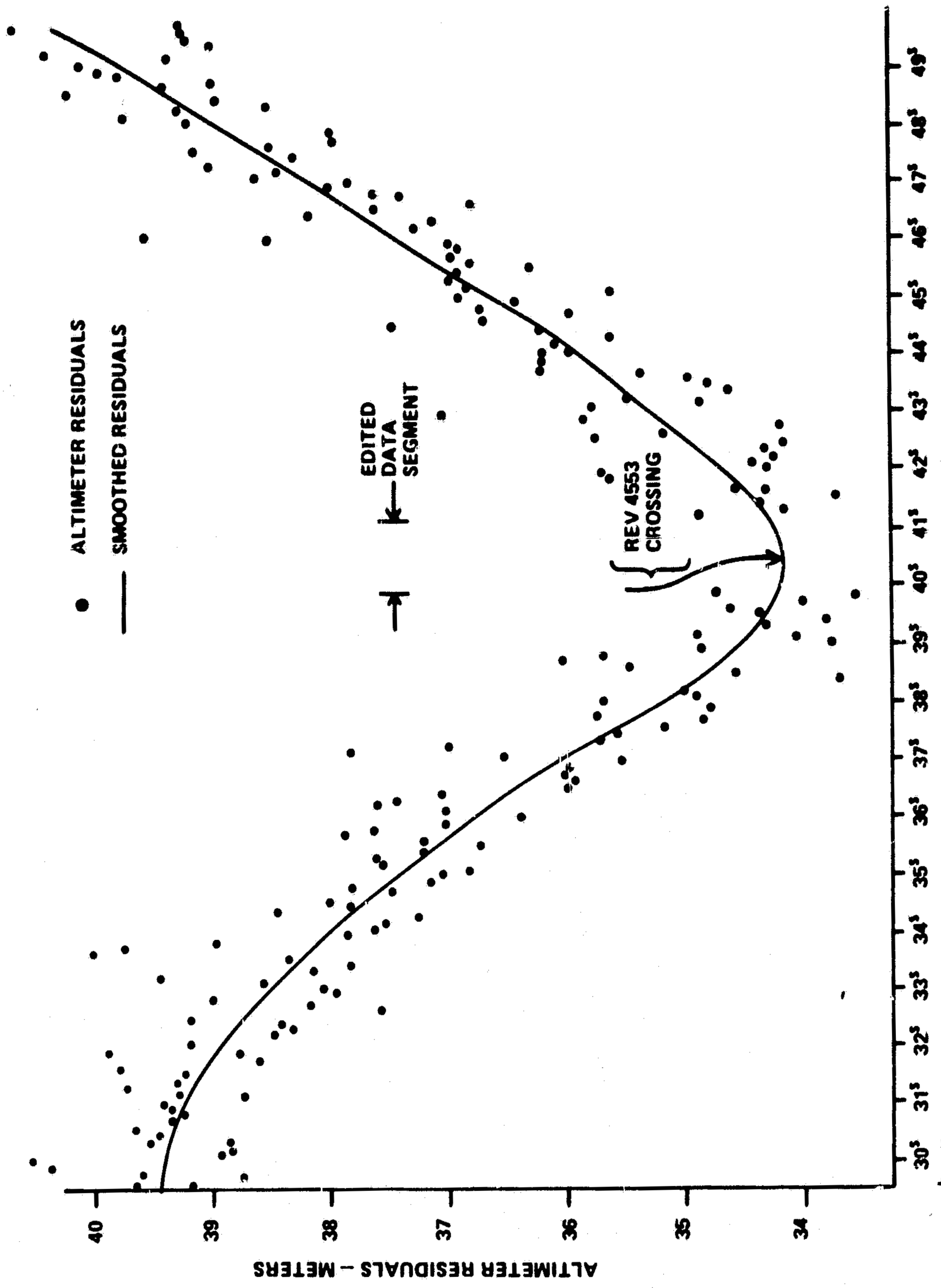

Figure 6. Altimeter Residuals Across Bermuda on GEOS-3 Rev 5471

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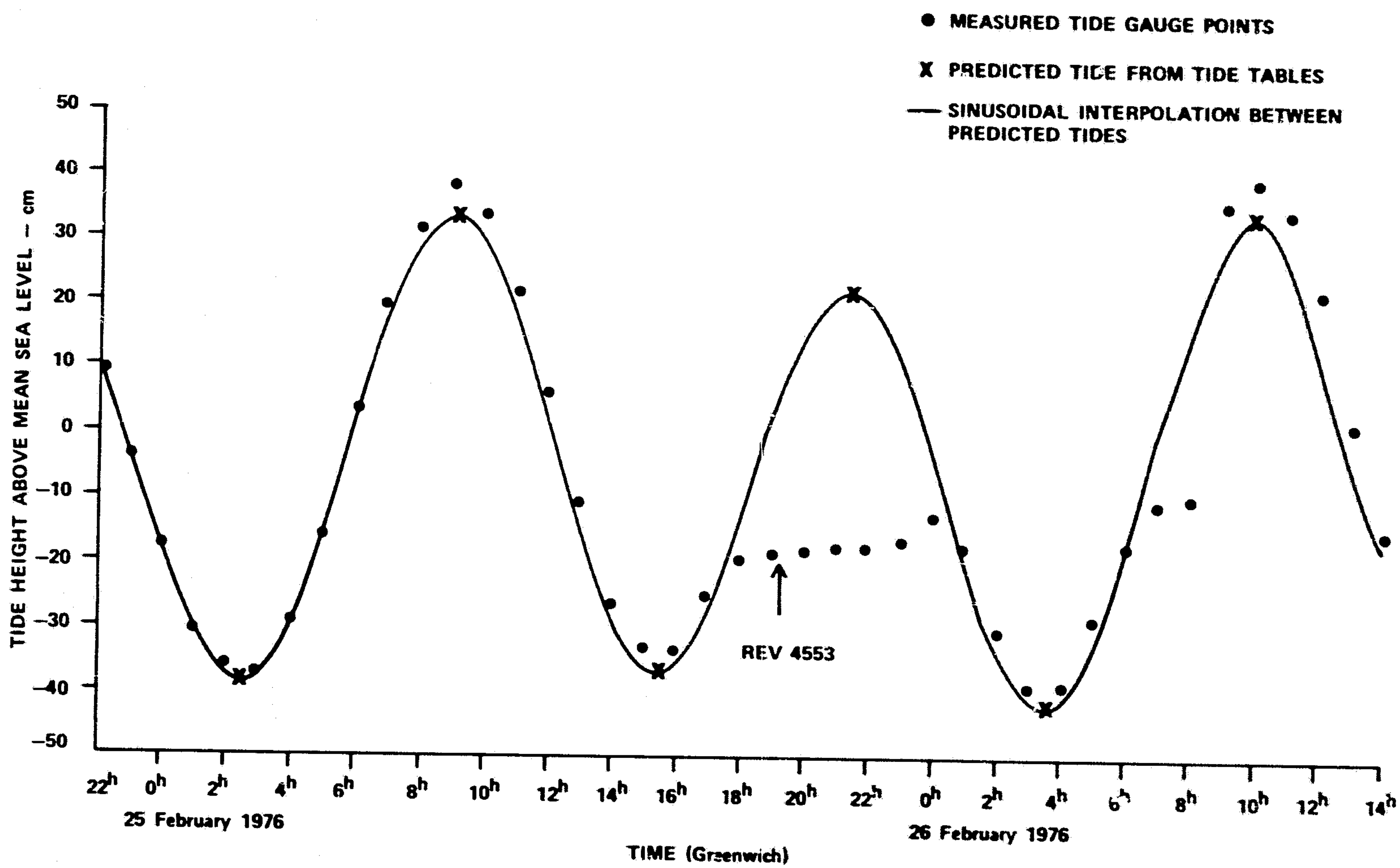

Figure 7. Measured and Predicted Tides at Bermuda Around Time of Crossing of GEOS-3 on Rev 4553

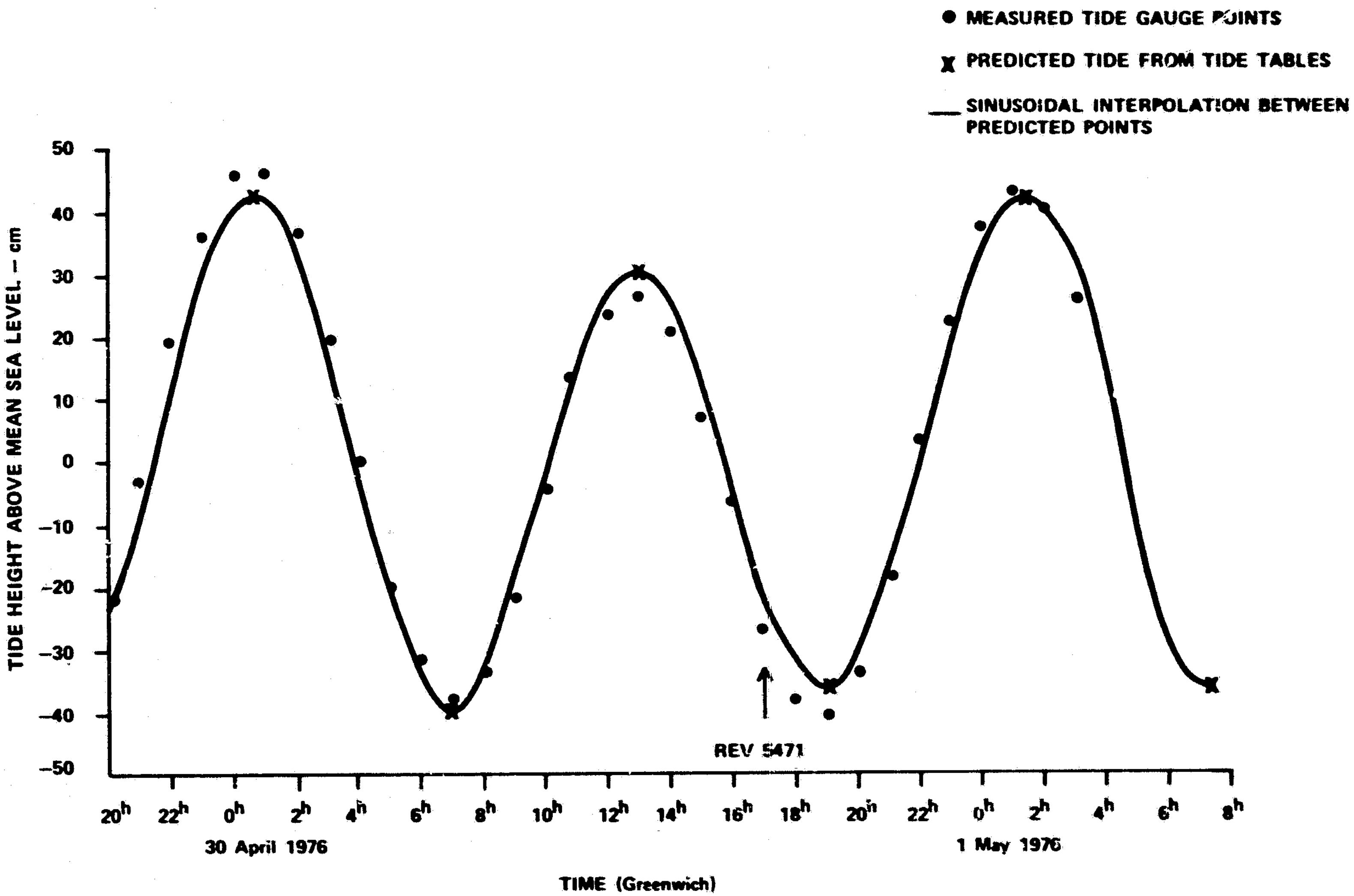

Figure 8. Measured and Predicted Tides at Bermuda Around Time of Crossing of GEOS-3 on Rev 5471

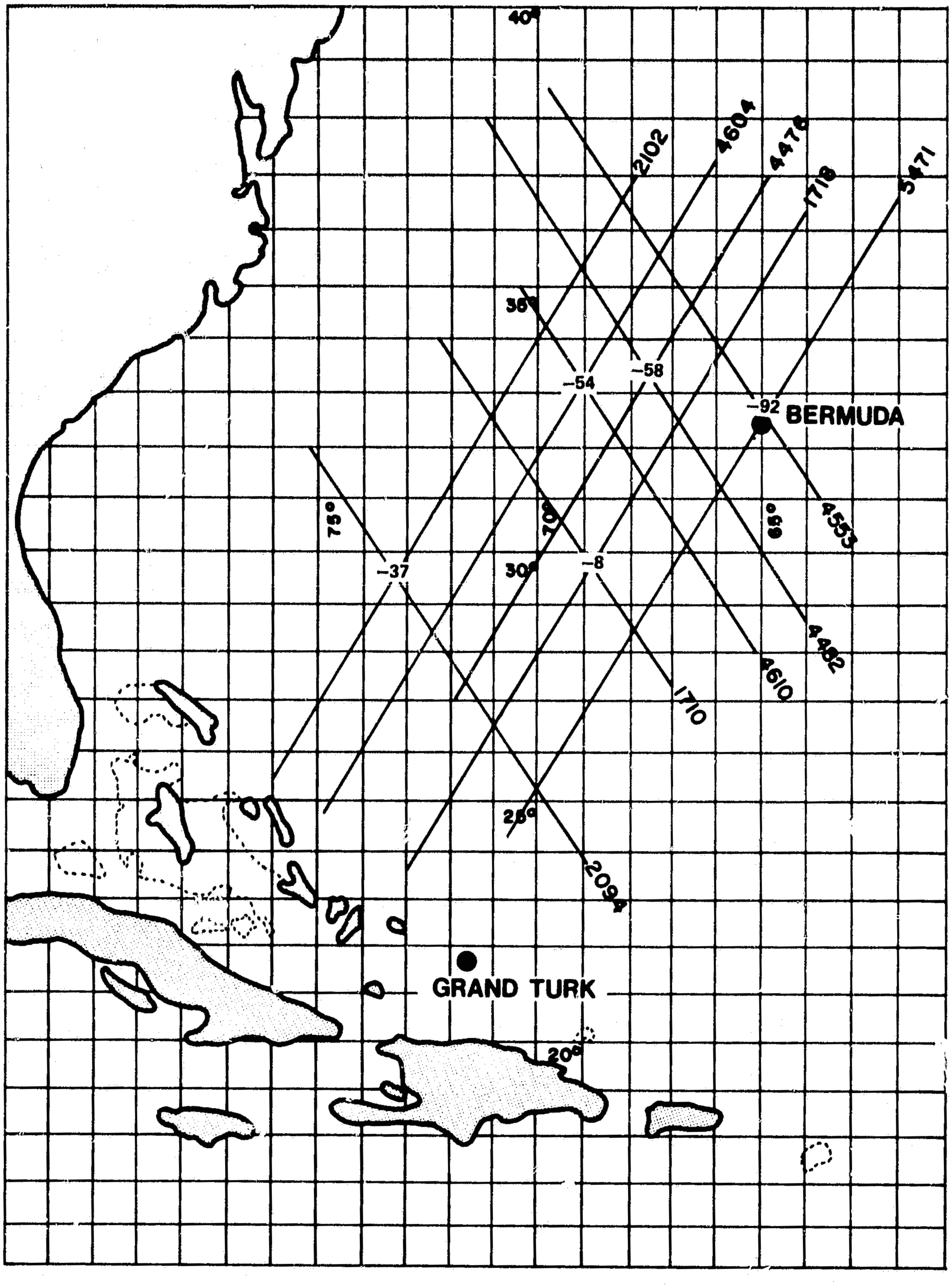

Figure 9. GEOS-3 Altimeter Crossovers Used in Timing Bias Estimation