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Estimation of Mean Sea Surfaces in the North Atlantic, the Pacific and the Indian Ocean Using GEOS-3 Altimeter Data

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Greenbelt, Maryland 20771

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ABSTRACT

The mean surfaces of several regions of the world's oceans have been estimated using GEOS-3 altimeter data. Included in these regions are the northwest Atlantic, the northeast Pacific off the coast of California, the Indian Ocean, the southwest Pacific, and the Philippine Sea. These surfaces have been oriented with respect to a common earth center-of-mass system by constraining the separate solutions to conform to precisely determined laser reference control orbits. The same reference orbits were used for all regions assuring continuity of the separate solutions. Radial accuracies of the control orbits have been demonstrated to be on the order of one meter. In the computation of these surfaces, the altimeter measured sea surface height crossover differences were minimized by the adjustment of tilt and bias parameters for each pass with the exception of laser reference control passes. The tilt and bias adjustments removed long wavelength errors which were primarily due to orbit error. Ocean tides were modeled, with the Estes, 1977, global tide model. For comparison purposes the Mofjeld, 1975, northwest Atlantic tide model was also used for the ocean tide evaluation. The resolution of the estimated sea surfaces varied

from 0.25 degrees off the east coast of the United States to about 2 degrees in part of the Indian Ocean near Australia. The rms crossover discrepancy after adjustment varied from 30 cm to 70 cm depending upon geographic location. Comparisons of the altimeter derived mean sea surface in the North Atlantic with the 5′ x 5′ GEM-8 detailed gravimetric geoid indicated a relative consistency of better than a meter.

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ILLUSTRATIONS (Continued)

ESTIMATION OF MEAN SEA SURFACES IN THE NORTH ATLANTIC, THE PACIFIC AND THE INDIAN OCEAN USING GEOS-3 ALTIMETER DATA

1.0 INTRODUCTION

In this paper we present a determination of the mean sea surface in several areas of the world. The sea surface heights above the reference ellipsoid were determined using data from the radar altimeter onboard the GEOS-3 satellite from launch in April 1975 to January 1977. The combination of this data with precise orbital position information derived from laser data has permitted us to calculate the sea surface height above a reference ellipsoid to submeter accuracy.

In the following sections, the method of sea surface computation will be presented, and the features of the resulting sea surface will be compared to known geographic features. Also, the differences of the sea surface in the northwest Atlantic relative to a previously computed detailed gravimetric geoid and the consistency of this surface with orbital data will be examined.

2.0 DATA AND COMPUTATION TECHNIQUE

The raw GEOS-3 altimeter data consists of 10 point/sec or 100 point/sec measurements grouped into variable-length (2-3 sec) frames. This data was smoothed over a frame using a quadratic polynomial to provide the approximately 1 point/sec data used in this analysis. Figure 1 presents a map of the altimeter ground tracks for the global set of data used. The altimeter data were corrected for: 1) the GEOS-3 altimeter measurement bias (Martin and Butler, 1977), 2) the ocean tides using the Estes tide model (Estes, 1977), and 3) ionospheric and tropospheric refraction.

The process of crossover adjustment was used to eliminate orbital errors and other time-varying error sources (e.g., changes in the sea surface height due to tides, storms, etc.) from the determination of the mean sea surface.

The technique initially involved finding the locations of the intersection points of the ascending and descending passes of GEOS-3. The data files were then scanned to find the approximate time and location of each crossover. A quadratic interpolation using data extending to 0.2° on either side of the crossover was used to obtain the precise time, latitude and longitude of the crossover. The values of the sea surface height measurements for both the ascending and descending passes were similarly interpolated in time and were separately evaluated at the calculated crossover time. This procedure yielded a data set consisting of the time, latitude and longitude of the crossover point and the altimeter-derived sea surface height measurements at that point obtained on the ascending and descending passes.

The sea surface height crossover differences (= ascending pass height − descending pass height) were then used in a least squares adjustment process to compute a bias and a tilt for each pass, which were used to correct the sea surface measurements.

The adjustments which minimize the sum of the squares of the crossover differences will eliminate the relative errors in the sea surface heights, and will define the shape of the sea height surface. However, the adjustment does not provide any information on the orientation of the surface with respect to the center of mass of the earth. In order to fix the surface in space relative to the center of mass of the earth, six 5-day arcs of globally distributed laser data were held fixed in the solution. The groundtracks of the altimeter data contained within these 5-day arcs are presented in Figure 2.

These reference orbits were selected to maximize the global distribution of laser data and to obtain altimeter data from as many of the chosen ocean regions as possible in each arc. These orbits were computed using the laser station coordinates derived by Marsh, Williamson, and Martin, 1977, a value of GM = 398600.63 km^3/s^2, a value of the speed of light = 2.997925 x 10^8 m/s, and using both the GEM-10 (Lerch et al., 1977), and GEM-10B (Lerch et al., 1978), earth gravity models. After comparison between the GEM-10 and GEM-10B orbits, GEM-10B was chosen for the control orbits.

As a means of assessing the accuracy of these laser reference orbits, analyses of the laser residuals have been performed. These analyses consisted of solving for an apparent range bias and timing error for each pass of data in the final iteration of the orbit computation solution. These range biases and timing errors are intended to represent orbit errors and not tracking system errors. Figure 3 presents a histogram of the range biases for the orbits computed with the GEM-10 and GEM-10B gravity models. The SAO and GSFC data are kept separate due to the significantly greater accuracy of the GSFC data at this time. The data in Figure 3 indicates that the standard deviation of the range biases for the GSFC stations is reduced from 91 cm to 60 cm in going from GEM-10 to GEM-10B. The standard deviation of the range biases for the SAO passes increased from 147 cm to 187 cm in going from GEM-10 to GEM-10B. However in light of the noise level on this data, this increase is not considered to be significant.

Histograms of the apparent timing errors are presented in Figure 4. In this case the GSFC and SAO data have been combined. The mean value of the timing errors was reduced from 0.10 msec to nearly zero in going from GEM-10 to GEM-10B, however a slight increase of from 0.23 to 0.29 msec was noted in the standard deviations. This larger along track error is most likely due to increased errors in modeling the GEOS-3 14th order resonant coefficients in GEM-10B versus GEM-10 (private communication, Lerch, 1978).

Figure 5 presents histograms of the r.m.s. values of the laser residuals after removal of apparent range biases and timing errors. The overall rms values were 104 cm for the SAO data and 11.9 cm for the GSFC data. These rms values still contain the effects of orbit error which is not accounted for by the simple range bias and timing error model. It is noted that the analyses of the range biases and timing errors provide an indication of the orbit accuracy only in the vicinity of the tracking stations.

A further measure of the accuracy of the orbits has been provided by inspection of the altimeter sea surface height crossover differences in five of the six computation areas. This information is summarized in Table 1 where mean and rms differences are tabulated for the GEM-10 and GEM-10B orbits. In every case the rms difference is significantly lower for GEM-10B. In two cases the rms difference was reduced by a meter or more, in two cases the rms was reduced by 40cm and in one case the rms was reduced by 25cm. The overall rms was reduced from 195 cm for GEM-10 to 122cm for GEM-10B. Based upon this analysis and the analyses of the laser data, the GEM-10B orbits were adopted for the reference control grid.

Biases and tilts were computed for the remaining passes in a least squares adjustment process. These biases and tilts were then applied to the data and new crossover differences were computed. This correction procedure was repeated for several iterations. After each iteration, the rms crossover difference was computed. On the next iteration, any crossover difference whose magnitude was greater than 4 times the rms difference was flagged and was not used in computing the subsequent corrections. This editing procedure removed only a small number of points which had extremely large crossover differences. After the final iteration, the tilt and bias corrections were applied to the data of each pass, and the corrected sea surface height values were saved.

The contouring of the sea surface used the average at each crossover point of the ascending pass sea surface height and the descending pass sea surface height. The data points were gridded using a $(\text{distance})^{-4}$ weight function and the grid points were spaced at 0.25° in the northwest Atlantic and 2° in the other regions, which corresponds closely to the spacing of the crossover data. The surfaces are referenced to an ellipsoid of $a_e = 6378140$m and a flattening of 1/298.255.

Previous analyses, Marsh et al., 1978, have provided a contour map of the mean sea surface in the northwest Atlantic with a resolution of 0.25°. A plot of the altimeter ground tracks for this area is presented in Figure 6. Figure 7 presents histograms of the crossover differences before and after the adjustment. The rms of the differences has been reduced from 7 meters to 33cm. Notice also that the histogram of the raw data is skewed in the positive direction due to orbit error. This skewness has been removed by the adjustments, as the final histogram shows. It is noted that only 435 points have been edited from the total set of 23919 crossovers. In order to fix the surface in space relative to the center of mass of the earth, 14 passes of GEOS-3, which were tracked by 3 laser tracking stations in the calibration area, have been included in the solution. The ground tracks of these 14 passes are shown in Figure 8. These passes have very precise orbits because of the large amount of laser data used in the orbit determination, the sub-meter accuracy of the tracking station positions (Marsh, Williamson and Martin, 1977), and the excellent tracking geometry provided by the 3 laser tracking stations. The rms of the measurement residuals for these orbits was on the order of 10cm or less. The rms of the crossover differences from the set of 41 crossovers was 59cm. This number is not the result of any adjustment process, and should be compared to the 7 meter RMS of all the unadjusted orbits.

A very precise (~5cm) empirical ocean tidal model has been developed for a portion of the calibration area by Mofjeld, 1975. The area of coverage for this model is indicated by the shaded area in Figure 8. A global M_2 ocean tidal model developed by Hendershott, 1977, was used to supplement the Mofjeld model in this region. Table 2 presents a comparison of the altimeter crossover differences when the various tidal models were employed. The Mofjeld model is clearly superior to the other models in this area. The Estes model did show an improvement over not modeling the tides. Since the Hendershott model contains only the M_2 constituent and the Estes model is a global model containing all the major constituents, we have used the Estes model for global ocean tide computations.

Figure 9 shows the sea surface contour map derived from the GEOS-3 altimeter data with the orientation provided by the laser triple short arc orbits. Several features of the ocean floor topography are clearly reflected in the sea surface topography. Bermuda is clearly visible, and the long minimum in the center corresponds to the Hatteras abyssal plain. To the west, the Blake Bermuda Outer Ridge and the Blake Escarpment are visible. Lines indicating the 200m, 2000m and 4000m bathymetry contours have been added. Notice how the sea surface contours follow the 2000m line along the entire North American coastline. In the region of the Blake Bahama Outer Ridge, the 4000m line extends out into the Atlantic, and this feature is clearly shown in the contour lines of the sea surface.

In the North Atlantic, just south of the continental shelf, there appears in the sea surface contour a long feature which parallels the continental shelf and which does not seem to have any corresponding feature in the ocean floor topography. This feature may be due to the presence of the Gulf Stream in this area.

The 5′ x 5′ GEM-8 detailed gravimetric geoid (Marsh and Chang, 1978) covers a portion of the same area as the sea height surface presented here, and thus may be used for comparison with this surface. The Marsh-Chang geoid is a detailed gravimetric geoid presented on a 5′ x 5′ grid which incorporates both a satellite-determined geoid (GEM-8) and surface gravity anomaly data.

The differences after the adjustment of X, Y and Z were contoured and are shown in Figure 10. The rms difference after the adjustment was 1.11 meters. On Figure 10, areas with height differences greater than +1 meter and areas with height differences less than -1 meter have been indicated. These areas of large differences occur either at the edges of the sea surface area where it is expected that the solution is weak, or in the southernmost portion of the surface, where the surface is very convoluted due to the presence of many islands and bathymetric features.

To check the consistency of the calculated sea surface in the northwest Atlantic with the orbital and altimeter data which were used in the sea surface computation, we have compared the sea surface heights from our calculated sea surface with the sea surface heights obtained directly from the altimeter measurements of several passes. The difference in the two sea surface heights should indicate both the short wavelength time-dependent errors due to eddies, storms, etc., and long wavelength orbital errors which should appear as biases and tilts in the height differences.

Figure 11 shows the height differences (residuals) plotted every second for a short arc of 8 minutes duration observed simultaneously by three lasers which was used as a control pass in the solution. The short arc data was used in the solution, and thus the mean of its residuals is nearly zero. However the individual residuals have magnitudes as large as 50 cm. These residuals for a single pass are attributed to noise in the altimeter data and the presence of unmodeled time dependent effects, which have been averaged out in the process of computing the mean sea surface.

Figures 12, 13, 14 and 15 present altimeter residuals for four other passes of data simultaneously observed by three lasers. These altimeter passes were not used in the computation of the surface and thus provide an independent means of assessing the accuracy of the surface as well as the accuracy of the orbits. The residuals are generally on the order of a meter or less with mean values varying from about 40 to 90 cm. The reason for the positive nature of the residuals is not known, however these four passes were recorded at a different time from the control passes.

Also shown in Figure 11 are the residuals for the same pass when the orbit was computed using a five day arc of laser data. The residuals show a mean offset of about 50 cm which is attributed to radial error in this portion of the five day orbit. Figure 16 presents plots of altimeter residuals for three other passes during the same five day orbit. These residuals indicate orbit errors which are generally less than 50 cm. Some of the systematic trends noted in the residuals, e.g., at 23^m and 24^m on the 13^h pass may be due to oceanographic phenomena.

This analysis and the control pass crossover analysis presented in Table 1 have provided the rationale for the use of five day orbits for control passes in orienting the mean sea surfaces.

In the computation of the mean sea surface in the northwest Atlantic using five day arcs as control orbits, the geographic area selected was larger than that used earlier. A comparison of this surface with the previous solution, oriented using short arc laser orbits, showed a mean difference of 31 cm and an rms difference of 54 cm. This high level of agreement has thus provided confidence that the five day arcs are accurate enough to provide global orientation for the other mean sea surfaces.

Figure 17 through 22 present contour maps of the mean sea surface in each of the following regions: the northwest Atlantic, the northeast Pacific, the southwest Pacific, the Philippine Sea, and the Indian Ocean.

CONCLUSIONS

Using radar altimetry and precise laser ranging data, techniques have been developed for the computation of mean sea surface on a global scale. Using these techniques mean sea surfaces have been computed for six areas of the earth's oceans. The spatial resolution achieved varies from 0.25° in the northwest Atlantic to 2° in some areas. The surfaces are referenced to the center of mass of the earth with an accuracy of about a meter and have relative accuracies ranging from 30 to 70cm.

REFERENCES

1) Estes, R. H., "A Computer Software System for the Generation of Global Tides Including Self-Gravitation and Crustal Loading Effects," GSFC Document X-920-77-82, April 1977.

2) Hendershott, M. C., "The Effects of Solid Earth Deformation on Global Ocean Tides," Geophysical Journal of the Royal Astronomical Society, 29, pp. 389–403, 1972.

3) Lerch, F. J., Klosko, S. M., Laubscher, R. E., and Wagner, C. A., "Gravity Model Improvement Using GEOS-3 (GEM 9 and 10)," GSFC Document X-921-77-246, 1977.

4) Lerch, F. J., Wagner, C. A., Klosko, S. M., Belott, R. P., Laubscher, R. E., and Taylor, W. A., "Gravity Model Improvement Using GEOS-3 Altimetry (GEM 10A and 10B)," presented at Spring Annual Meeting of the American Geophysical Union, Miami Beach, Florida, April 1978.

5) Lerch, F. J., Private Communication, 1978.

6) Marsh, J. G. and Chang, E. S., "5′ Detailed Gravimetric Geoid in the Northwest Atlantic Ocean," Marine Geodesy, Vol. 1, No. 3, June 1978.

7) Marsh, J. G., Williamson, R. G., and Martin, T. V., "Tracking Station Coordinate Investigation," Final Report of GEOS-3 Investigation presented at New Orleans, La., November 1977.

8) Marsh, J. G., Munteanu, M. J., Martin, T. V., McCarthy, J. J., and Chovitz, P. S., "Estimation of Mean Sea Surface in North Atlantic Using GEOS-3 Altimeter Data," presented at Spring Annual Meeting of the American Geophysical Union, Miami Beach, Florida, April 1978, abstract published in EOS, Vol. 59, No. 4, 1978.

9) Martin, C. F., and Butler, M. L., "Calibration Results for the GEOS-3 Altimeter," Planetary Sciences Department Report No. 006-77, EG&G/WASC, 1977.

10) Mofjeld, H. O., "Empirical Model for Tides in the Western North Atlantic Ocean," NOAA Technical Report ERL 340-AOML 19, 1975.

Table 1
Altimeter Crossover Differences for
Laser Reference Control Passes

Area	No. of Crossovers	Mean (cm)		rms (cm)	
		GEM-10	GEM-10B	GEM-1C	GEM-10B
North West Atlantic Ocean	131	-45	-29	136	96
North East Pacific	18	-101	-110	224	170
Philippine Sea	61	-68	-76	162	137
Western Indian Ocean	56	2	-39	186	87
South West Pacific Ocean	78	128	46	286	153

Table 2
Ocean Tidal Model Evaluation
Sea Surface Height Crossover Differences in the GEOS-3
Calibration Area Based Upon Short Arc Orbits with
Simultaneous Tracking by Three Lasers

Tidal Model Used	Crossovers Inside The Mofjeld Area	Crossovers Outside The Mofjeld Area
Mofjeld/Hendershott	-17 ± 40 cm	2 ± 52 cm
Estes	-14 ± 59	12 ± 58
None	-13 ± 68	-2 ± 60

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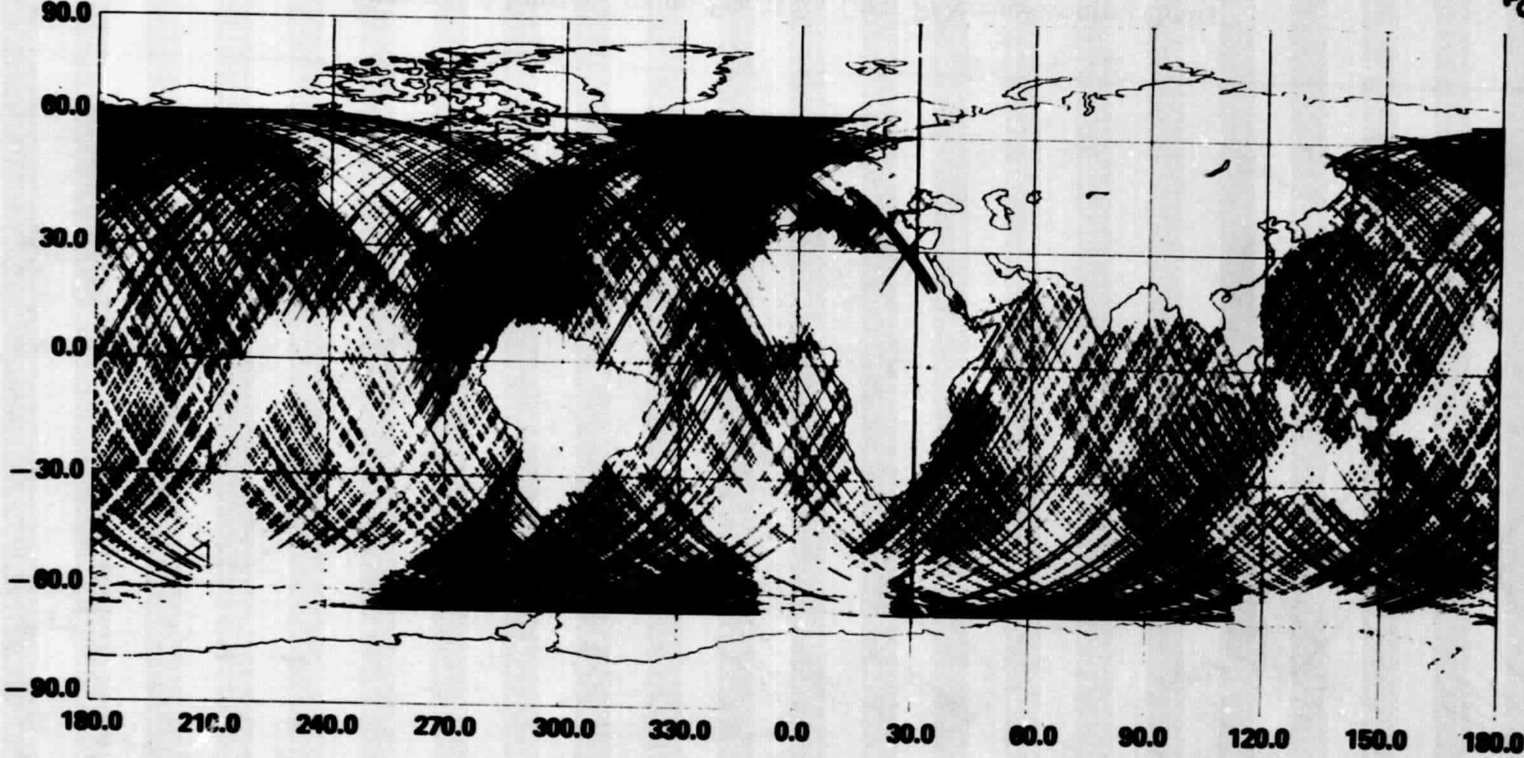


Figure 1. GEOS–3 Altimeter Data Available at GSFC January 1978

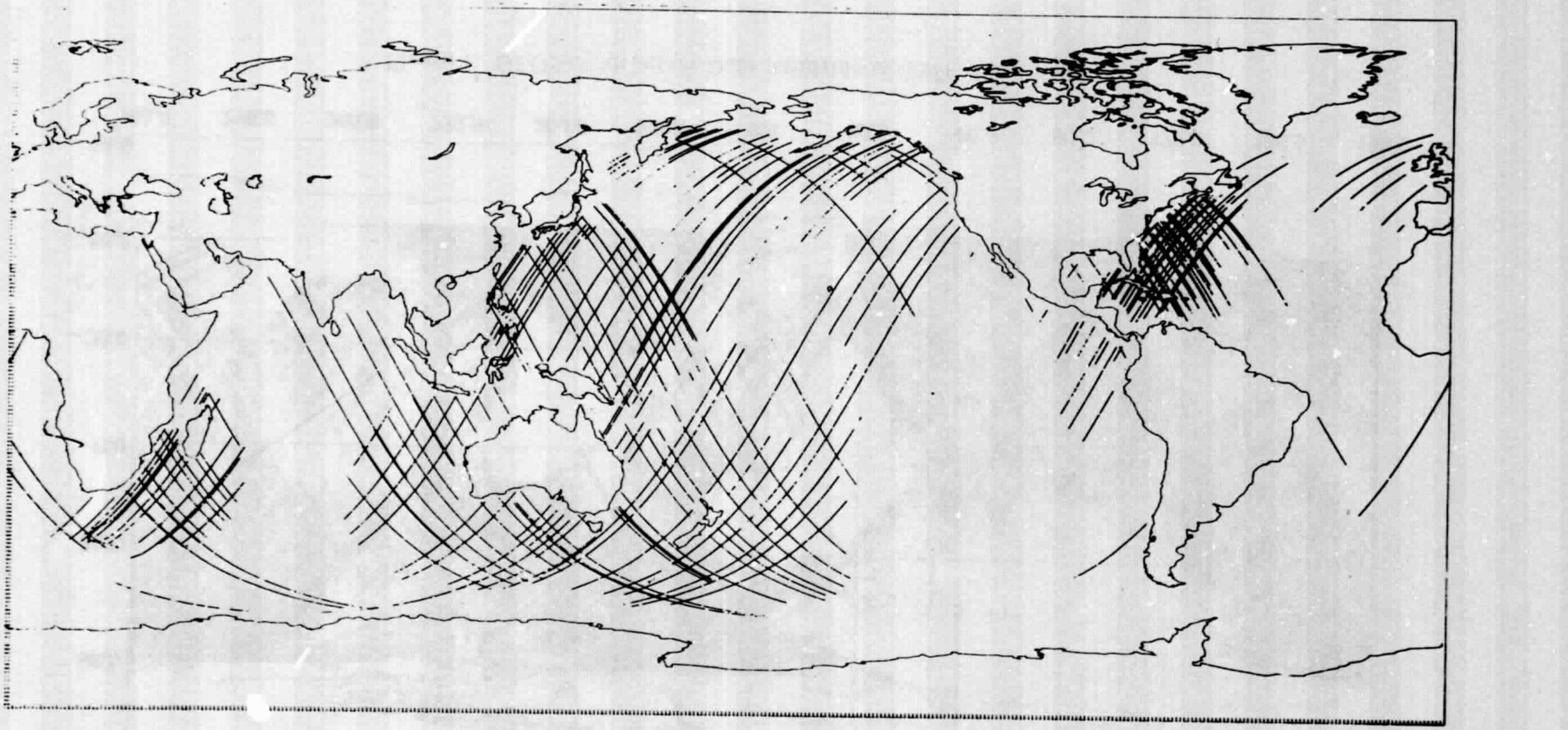


Figure 2. Altimeter Ground Tracks for Laser Reference Control Orbits

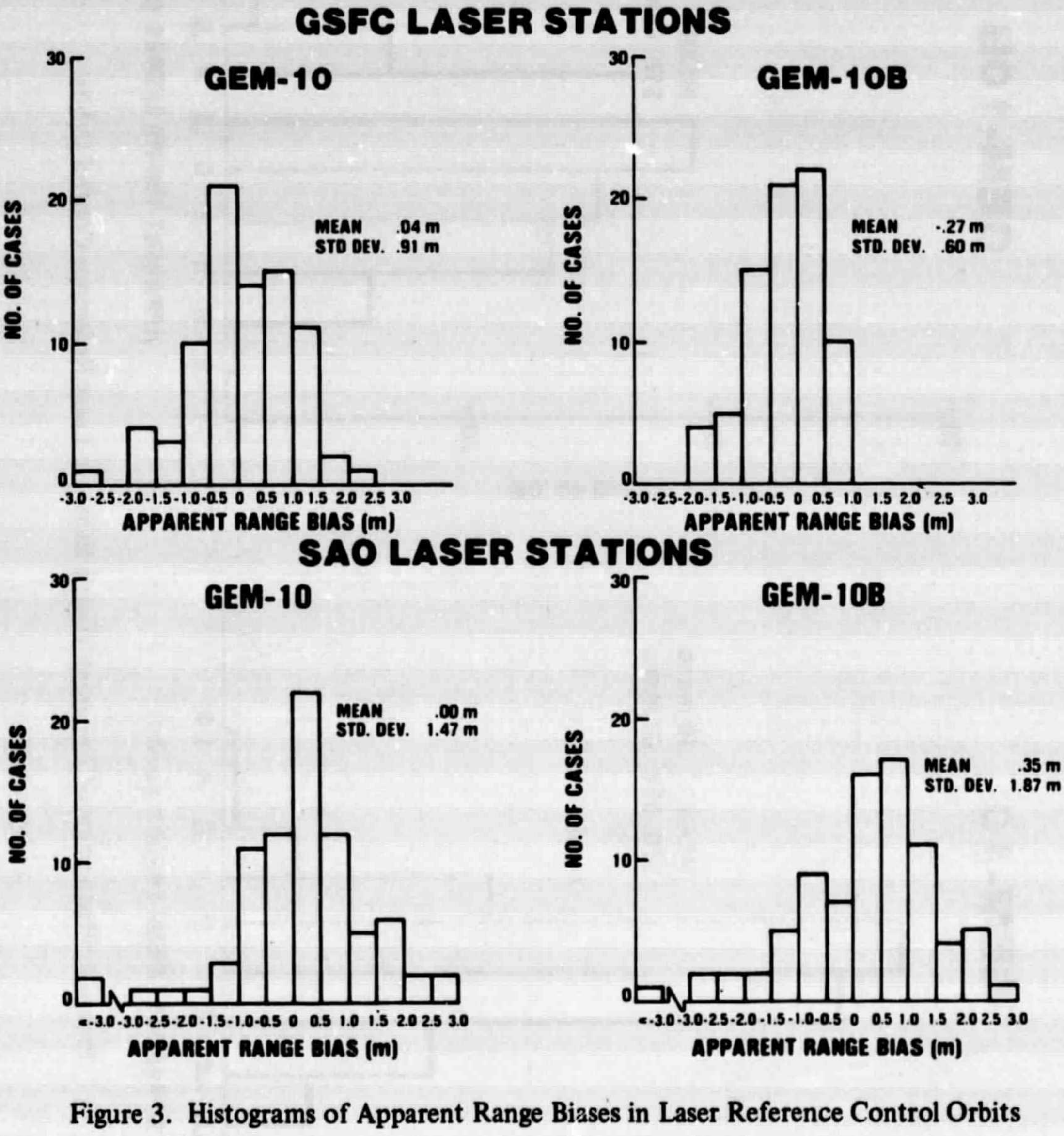


Figure 3. Histograms of Apparent Range Biases in Laser Reference Control Orbits

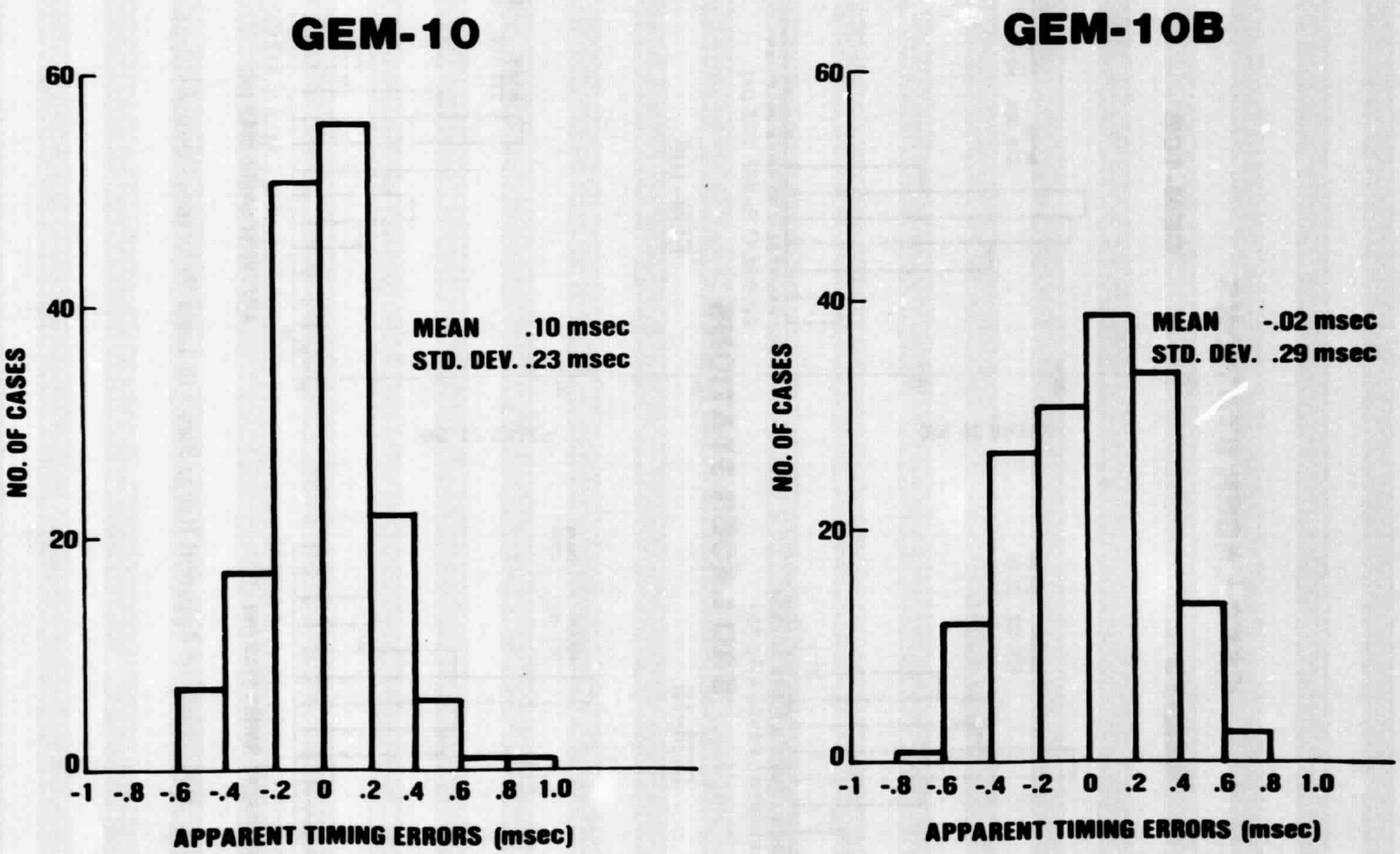


Figure 4. Histograms of Apparent Timing Errors in Laser Reference Control Orbits

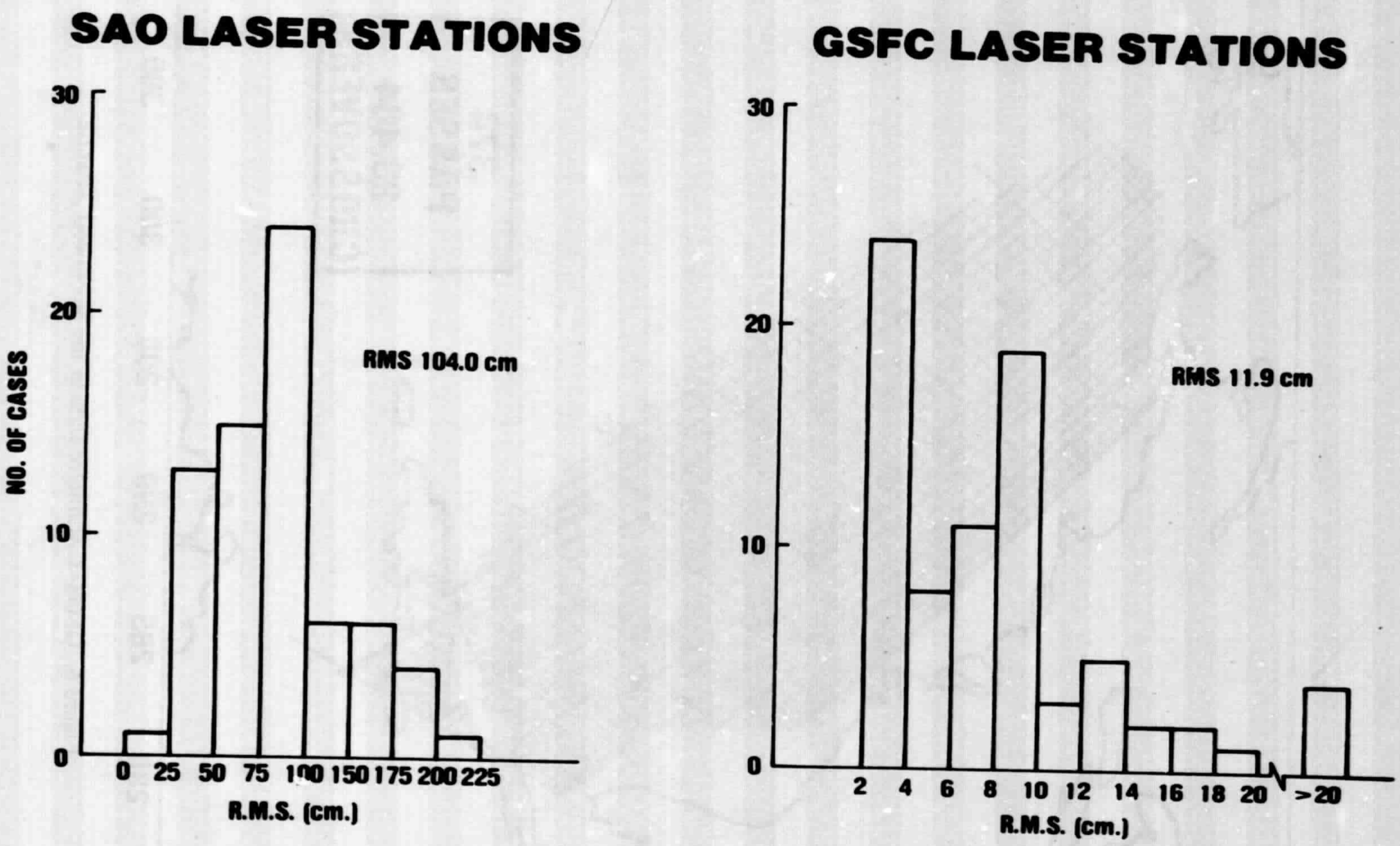


Figure 5. R.M.S. of Laser Residuals in Reference Control Orbits after Removal of Apparent Timing Errors and Range Biases

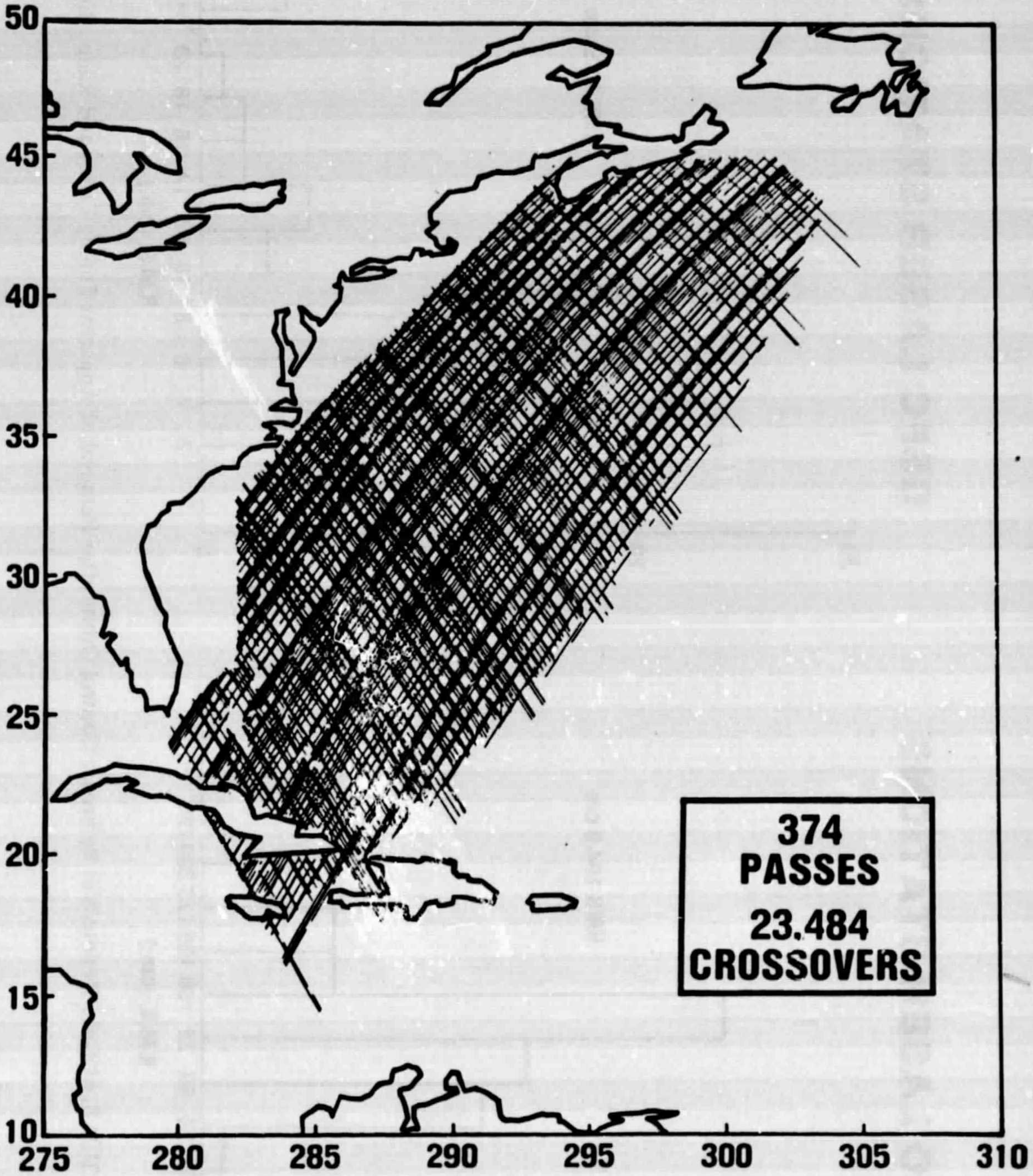


Figure 6. GEOS-3 Altimeter Data in the Northwest Atlantic

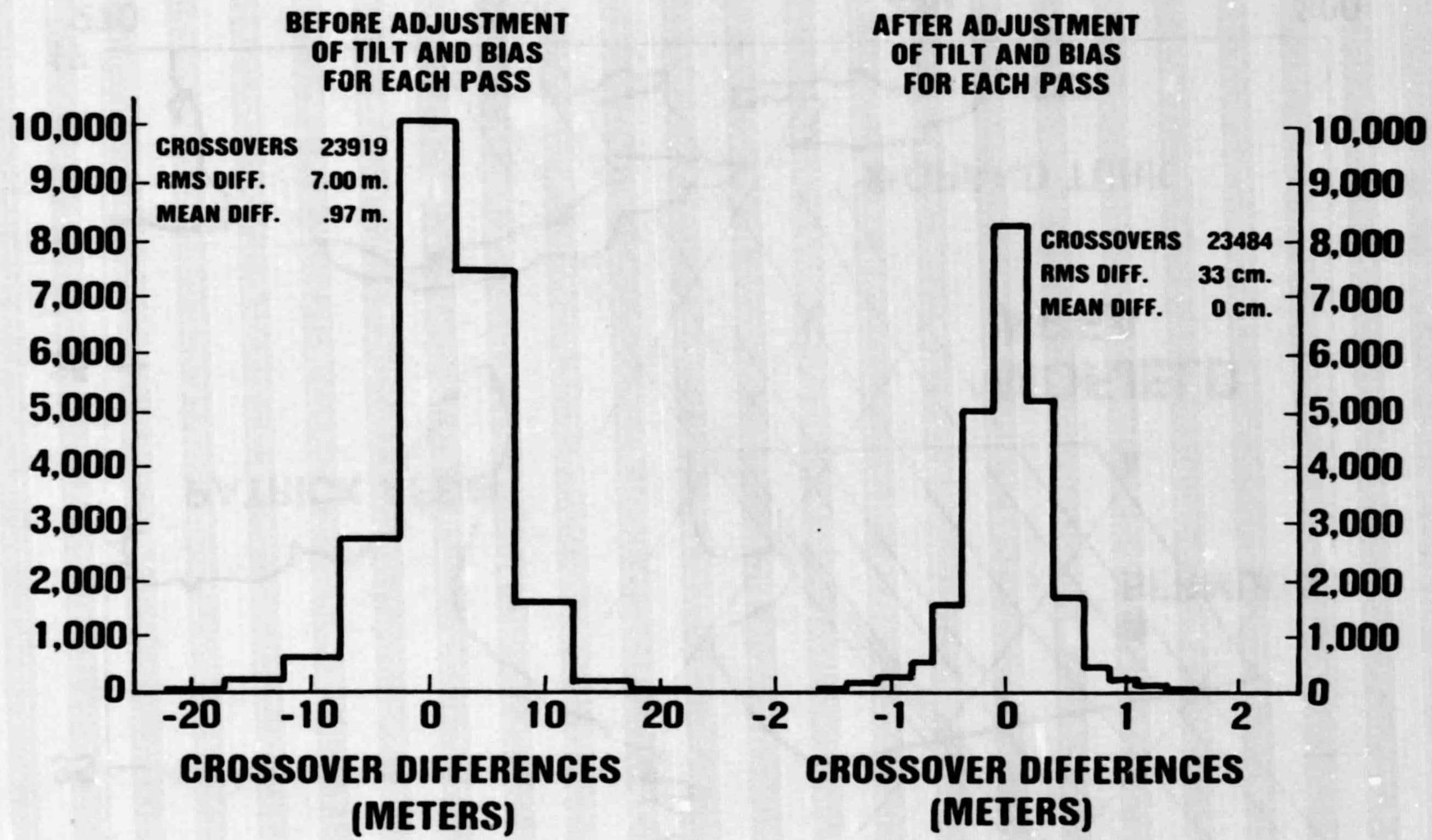


Figure 7. Histograms of Crossover Differences

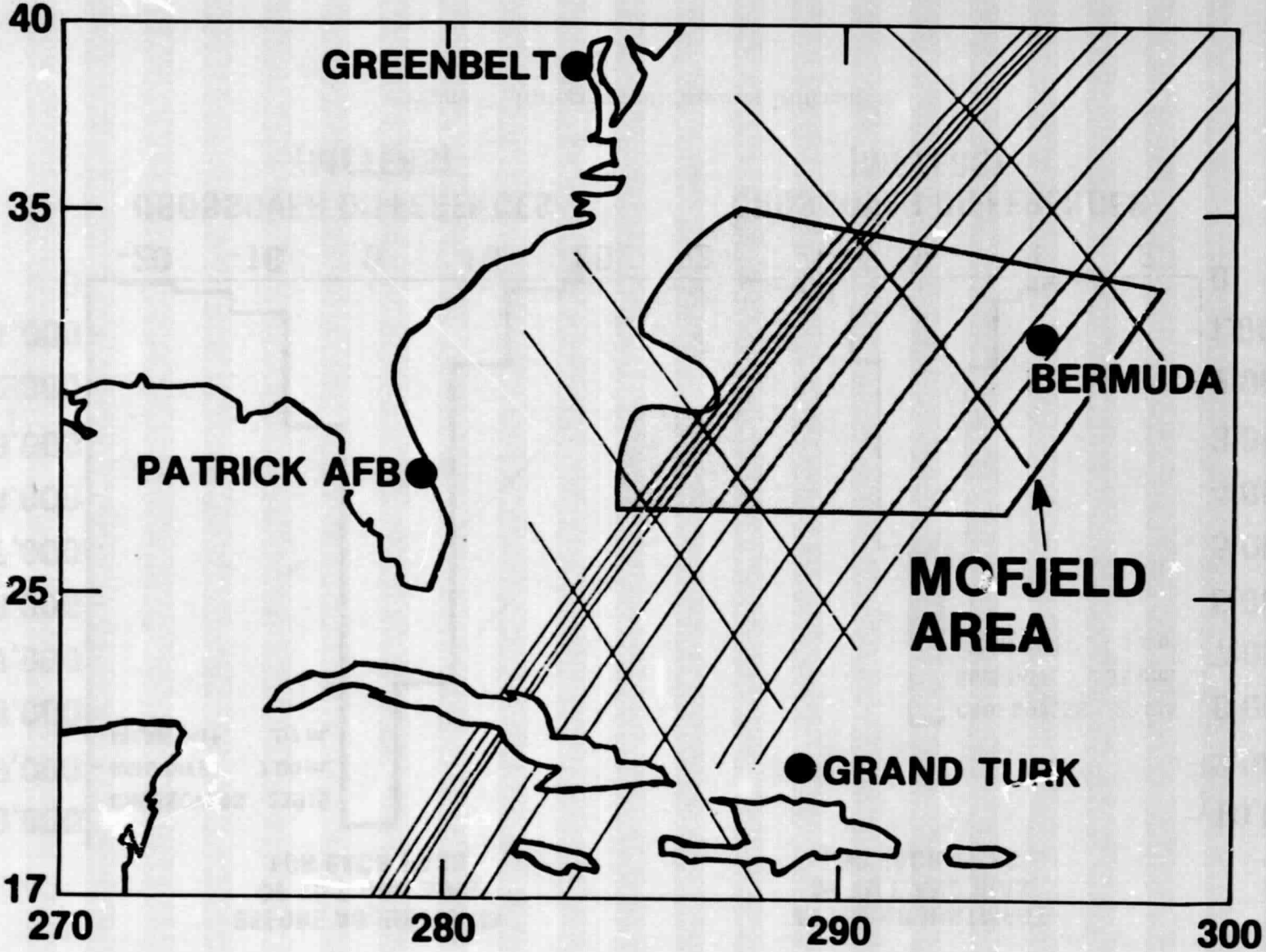


Figure 8. Laser Reference Control Passes

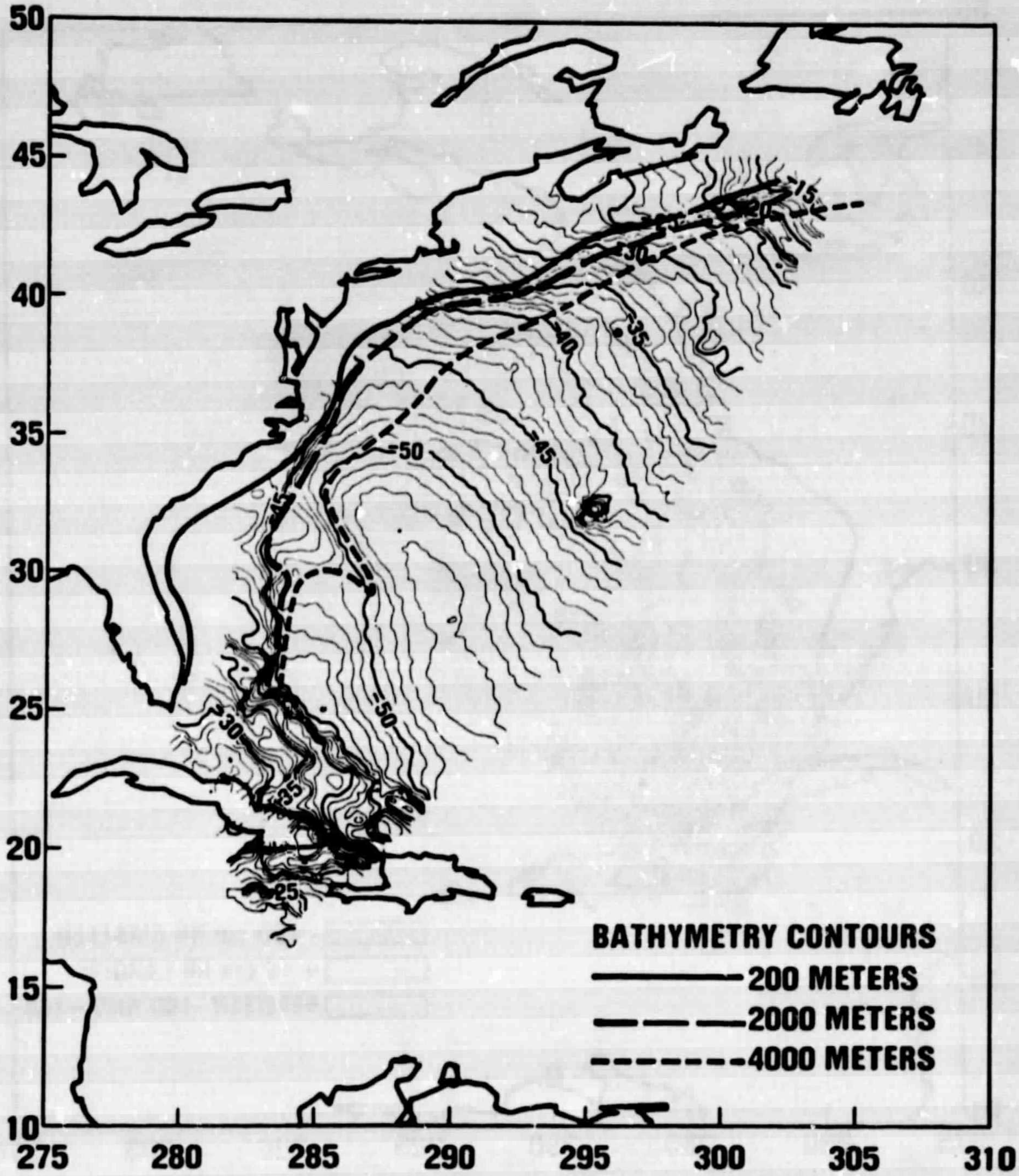


Figure 9. Contour Map of the Ocean Surface Derived from GEOS-3 Altimeter Crossover Data Contour Interval 1 Meter

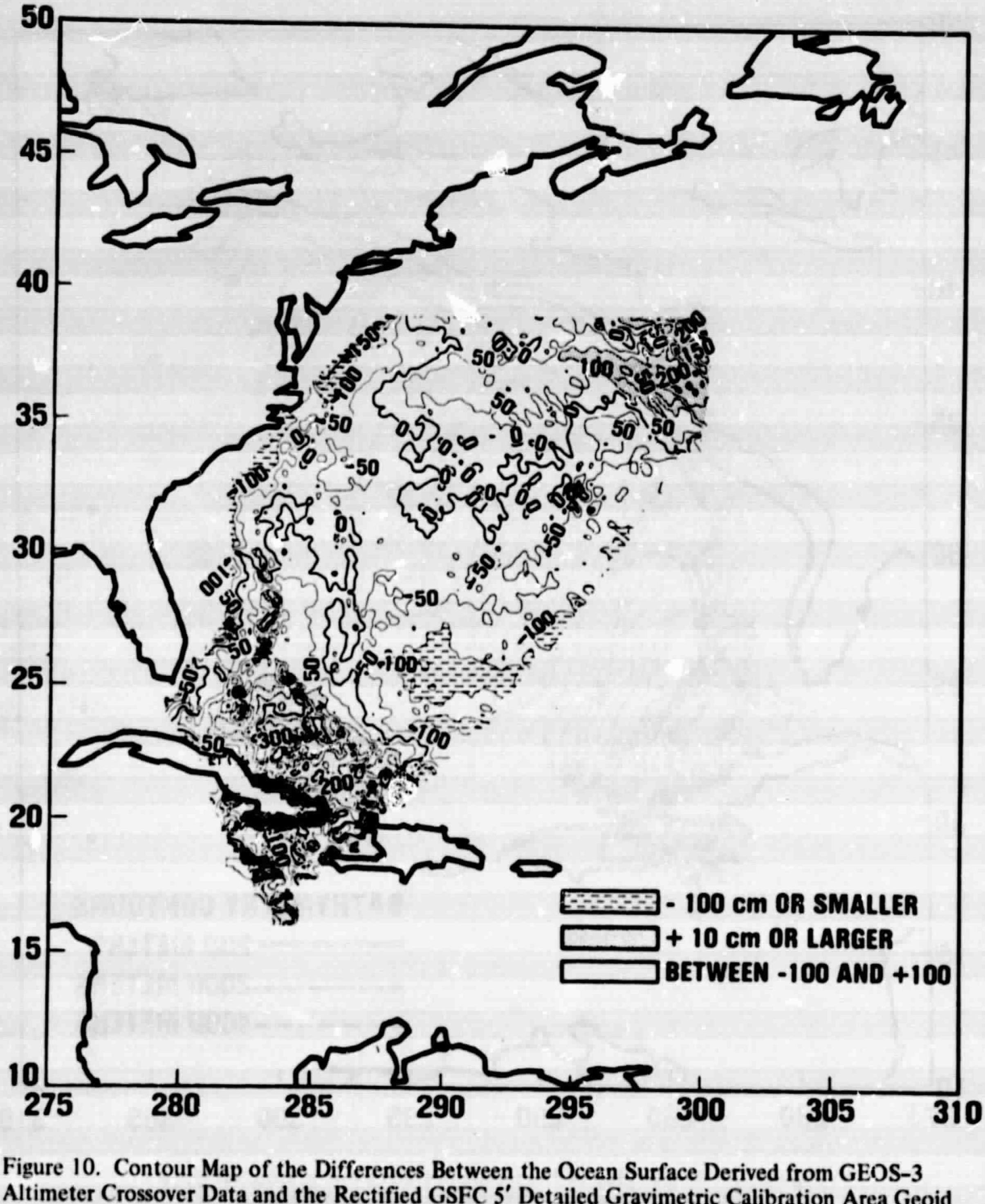


Figure 10. Contour Map of the Differences Between the Ocean Surface Derived from GEOS-3 Altimeter Crossover Data and the Rectified GSFC 5′ Detailed Gravimetric Calibration Area Geoid Contour Interval = 50 cm

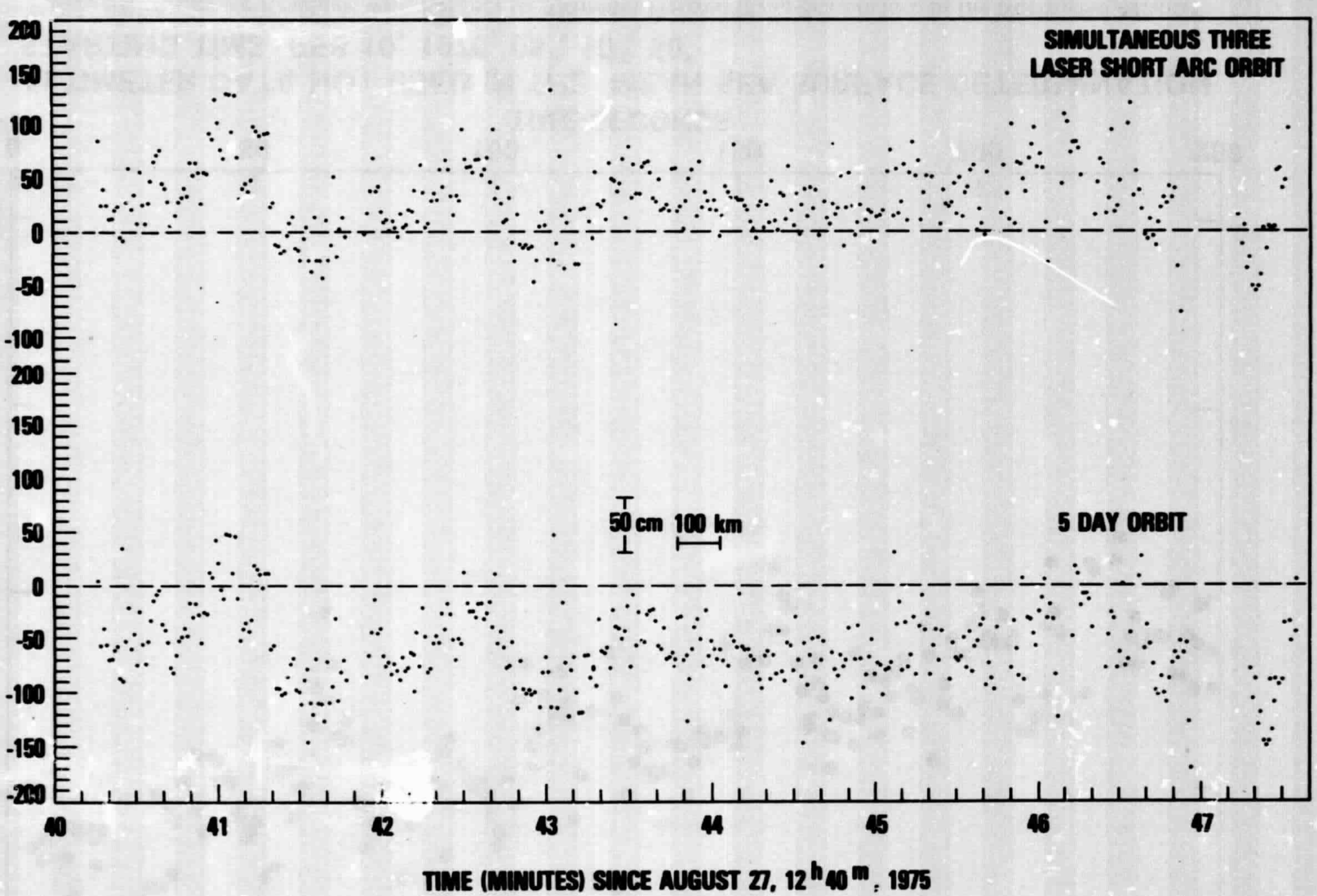
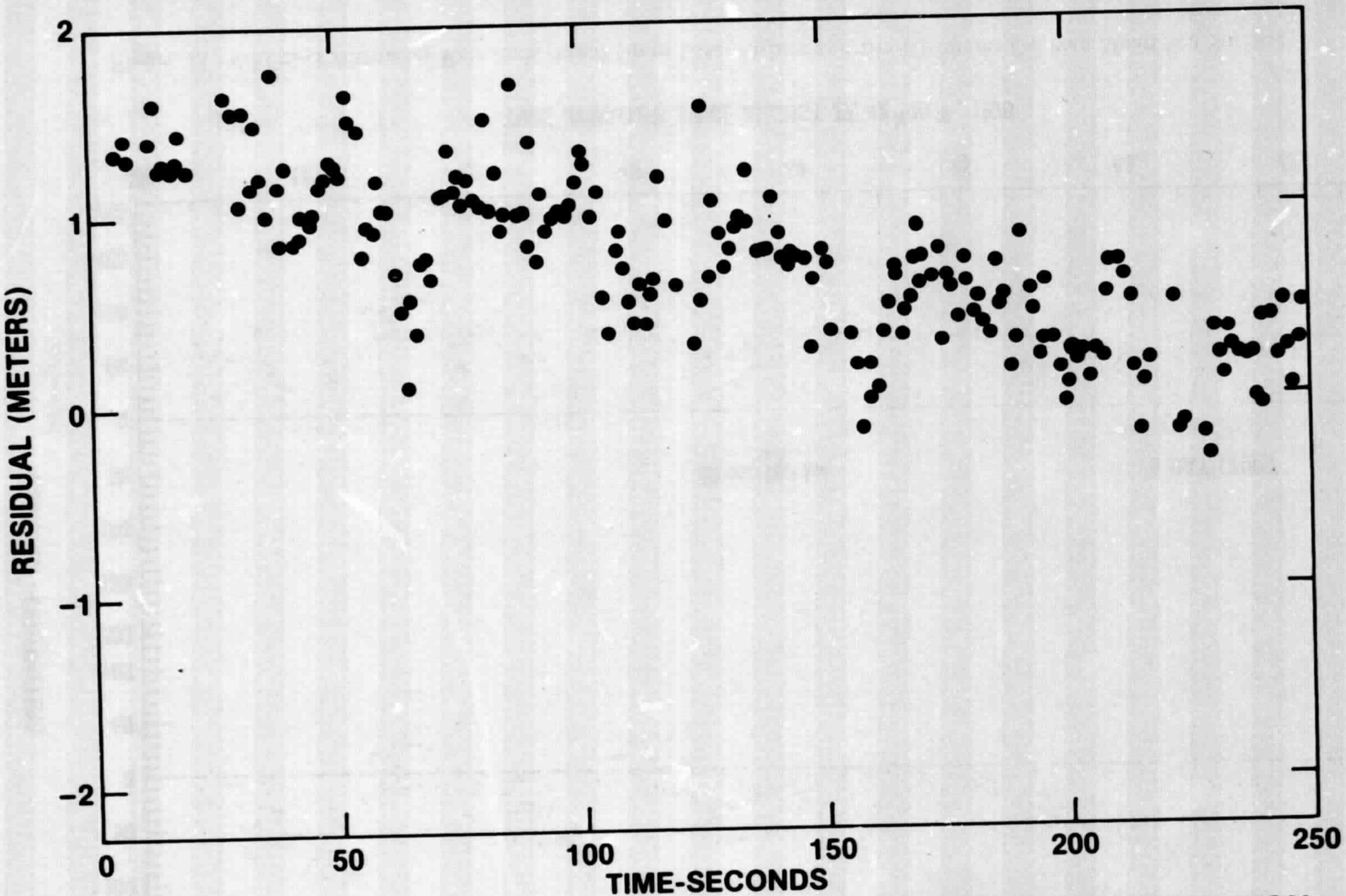


Figure 11. GEOS–3 Altimeter Residuals Based Upon Laser Orbits and the Altimeter Derived Mean Sea Surface



ALTIMETER DATA NOT USED IN THE MEAN SEA SURFACE DETERMINATION
STARTING TIME FEB 10, 1976, 08^h, 10^m, 50^s

Figure 12. Altimeter Residuals with Respect to Altimeter Derived Mean Sea Surface in the Northwest Atlantic Orbit Determined Using Simultaneous Tracking from Three Lasers

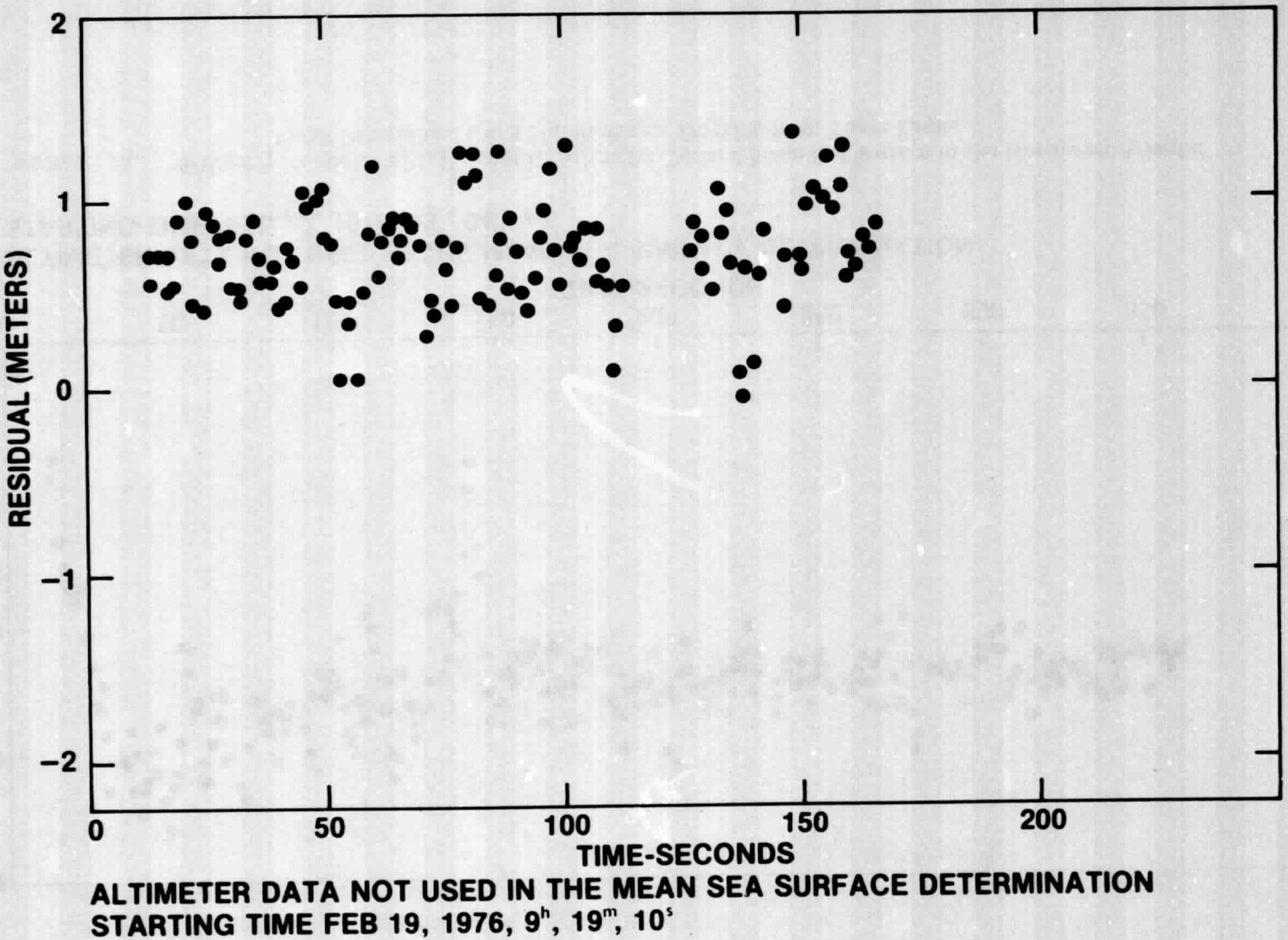


Figure 13. Altimeter Residuals with Respect to Altimeter Derived Mean Sea Surface in the Northwest Atlantic Orbit Determined Using Simultaneous Tracking from Three Lasers

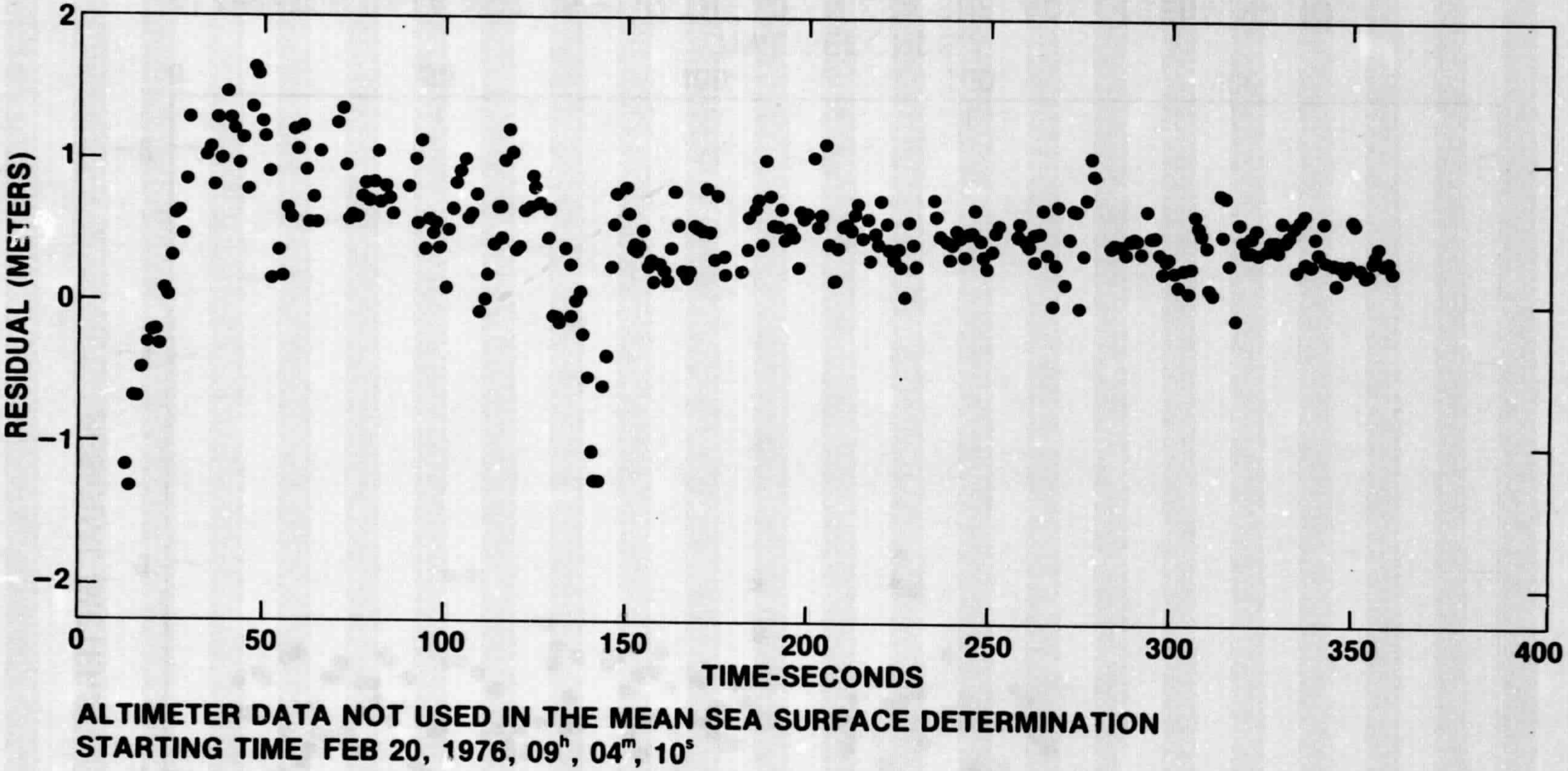
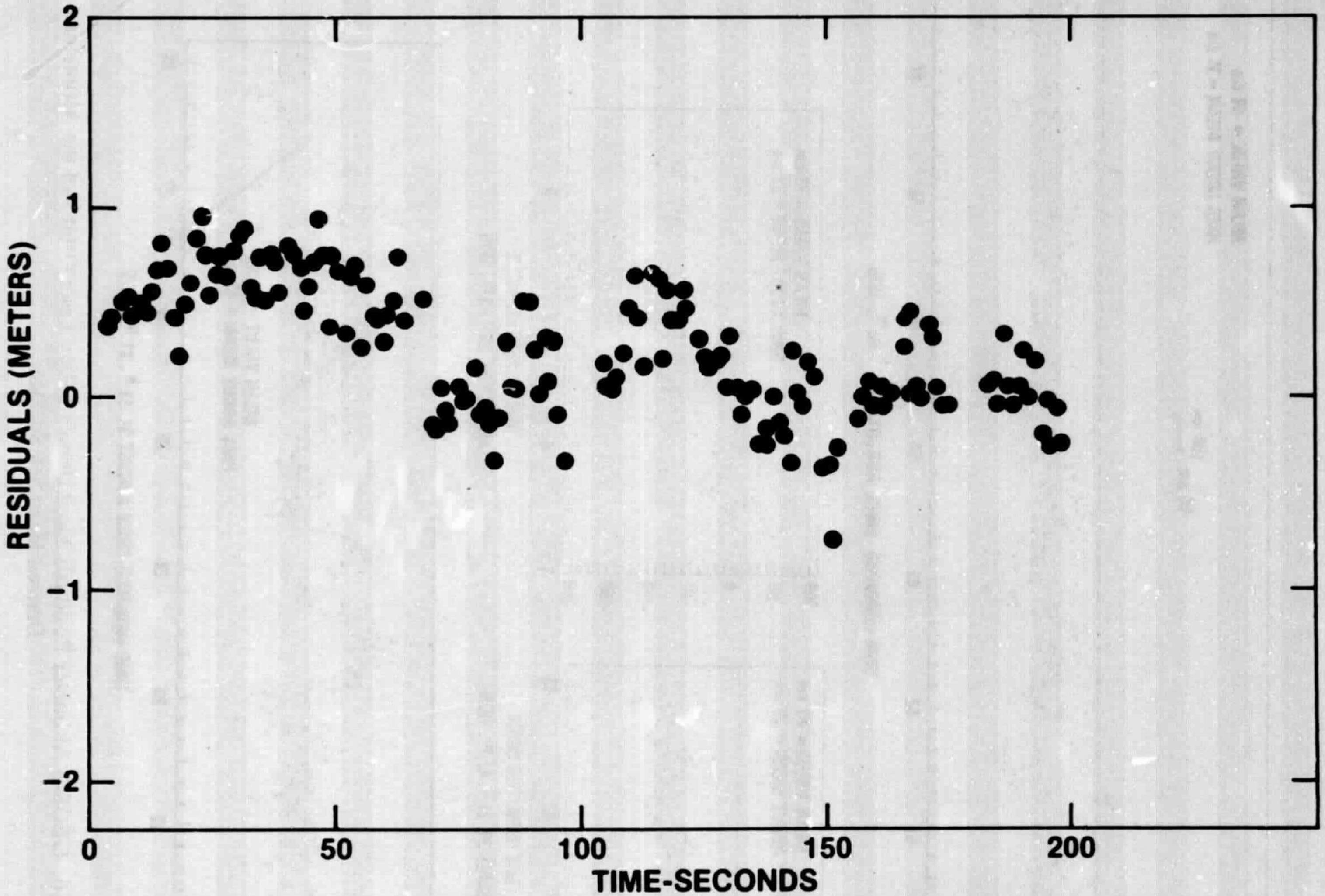


FIGURE 14. Altimeter Residuals with Respect to Altimeter Derived Mean Sea Surface in the Northwest Atlantic Orbit Determined Using Simultaneous Tracking from Three Lasers



ALTIMETER DATA NOT USED IN THE MEAN SEA SURFACE DETERMINATION
STARTING TIME FEB 20, 1976, 18^h, 47^m, 30^s

Figure 15. Altimeter Residuals with Respect to Altimeter Derived Mean Sea Surface in the Northwest Atlantic Orbit Determined Using Simultaneous Tracking from Three Lasers

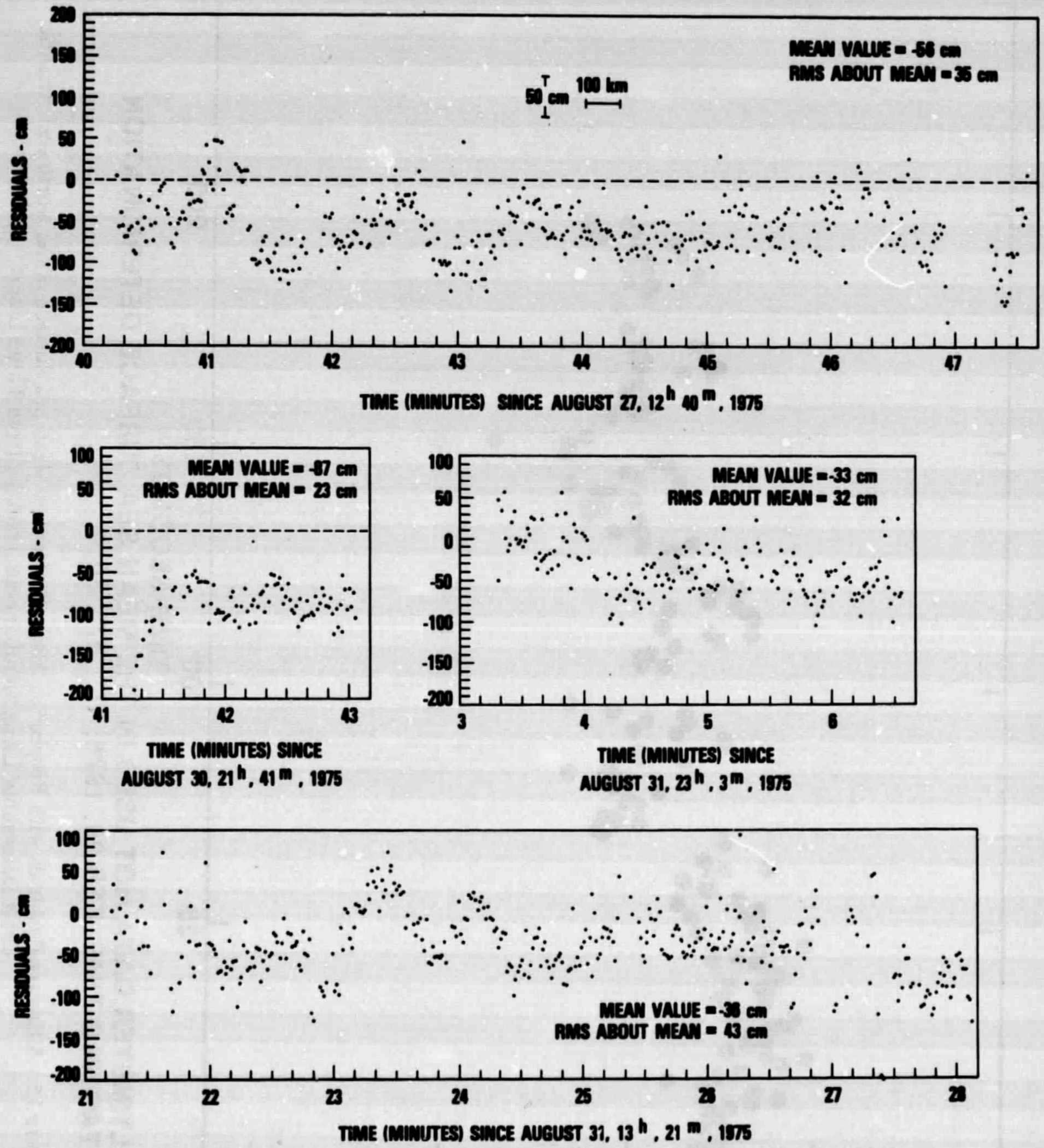


Figure 16. GEOS-3 Altimeter Residuals Based Upon a 5-Day Laser Orbit and the Altimeter Derived Mean Sea Surface

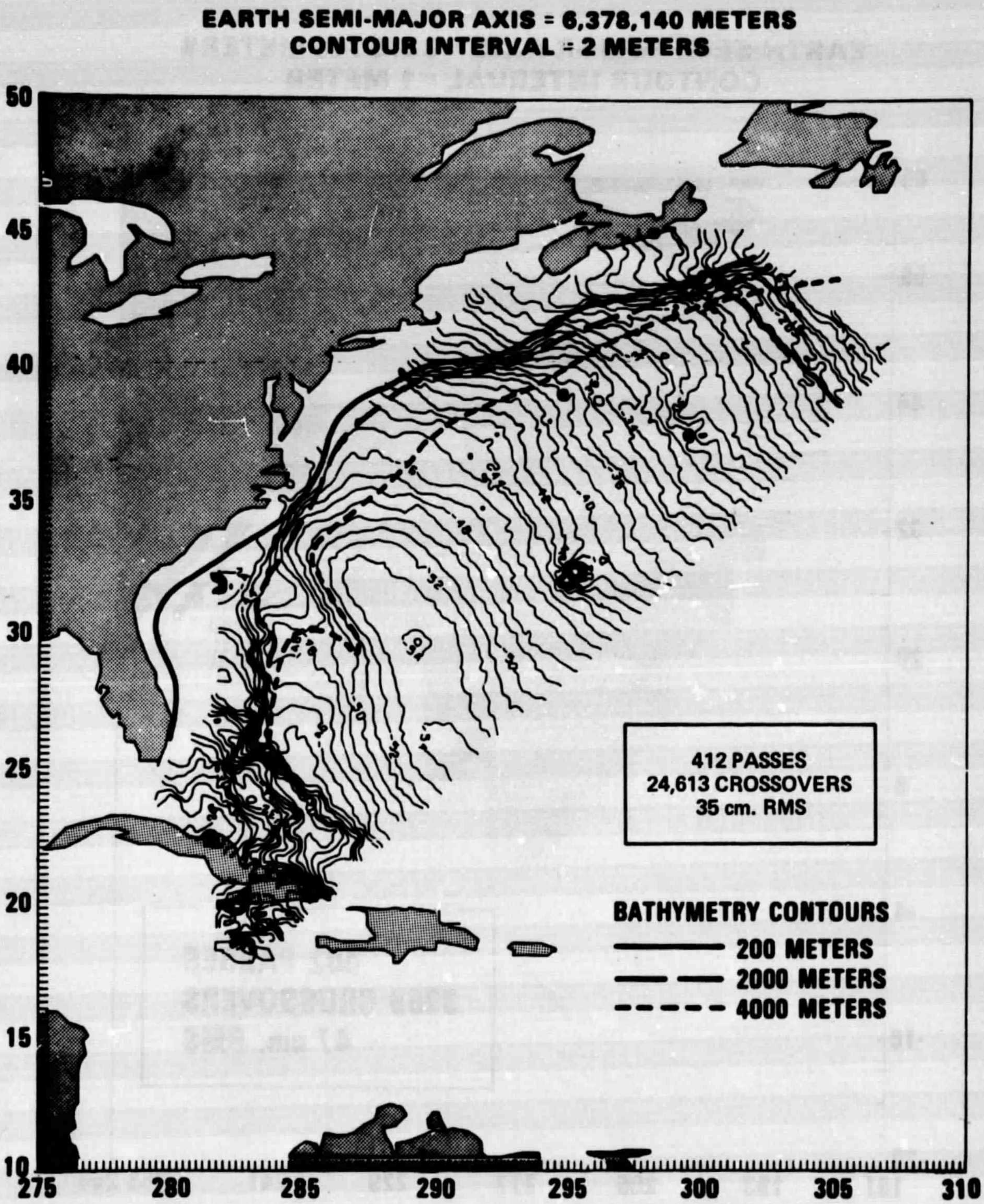


FIGURE 17. Contour Map of the Ocean Surface Derived from GEOS-3 Altimeter Crossover Data–Northwest Atlantic Ocean

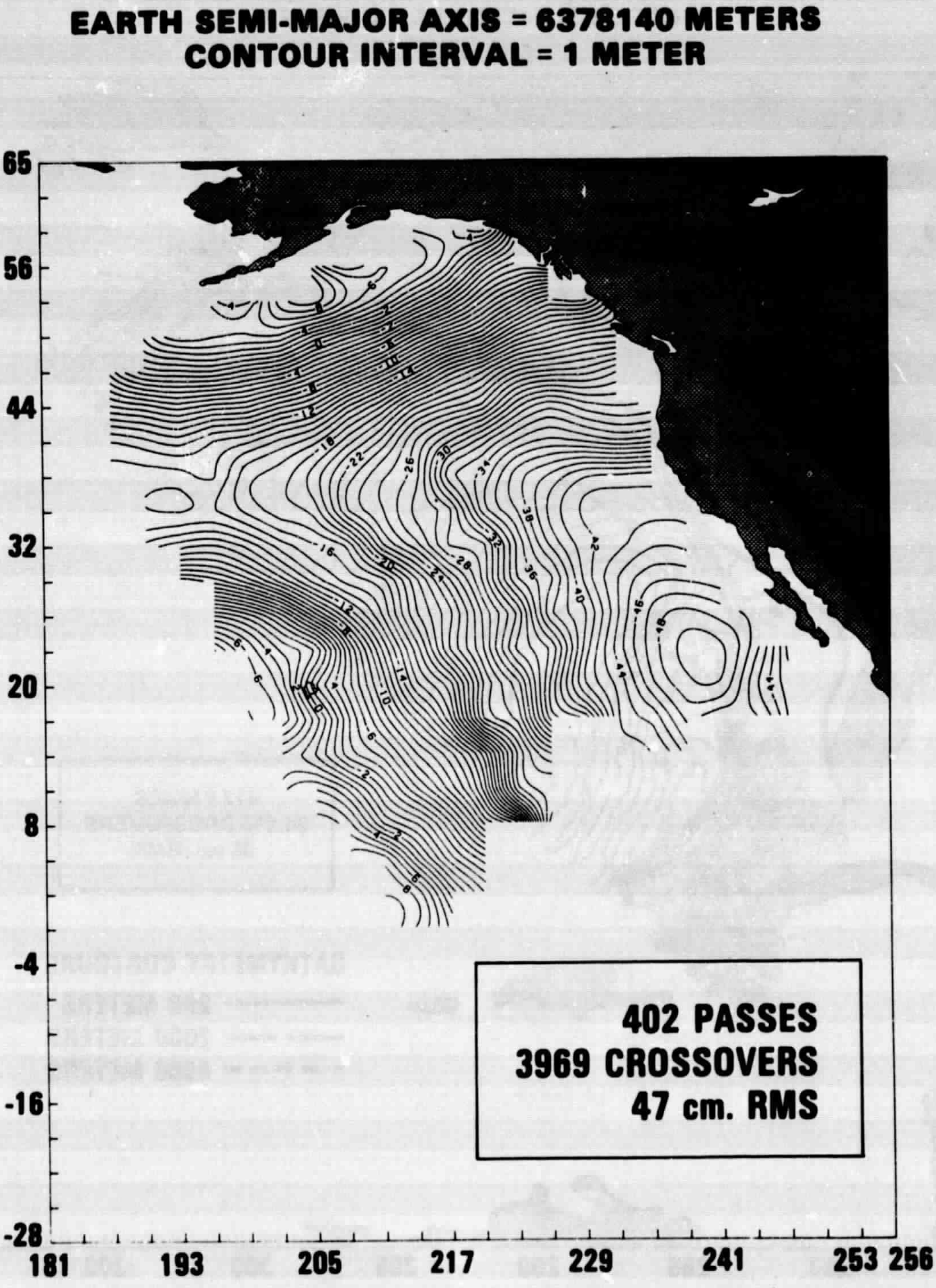


Figure 18. Contour Map of the Ocean Surface Derived from GEOS-3 Altimeter Crossover Data – Northeast Pacific Ocean

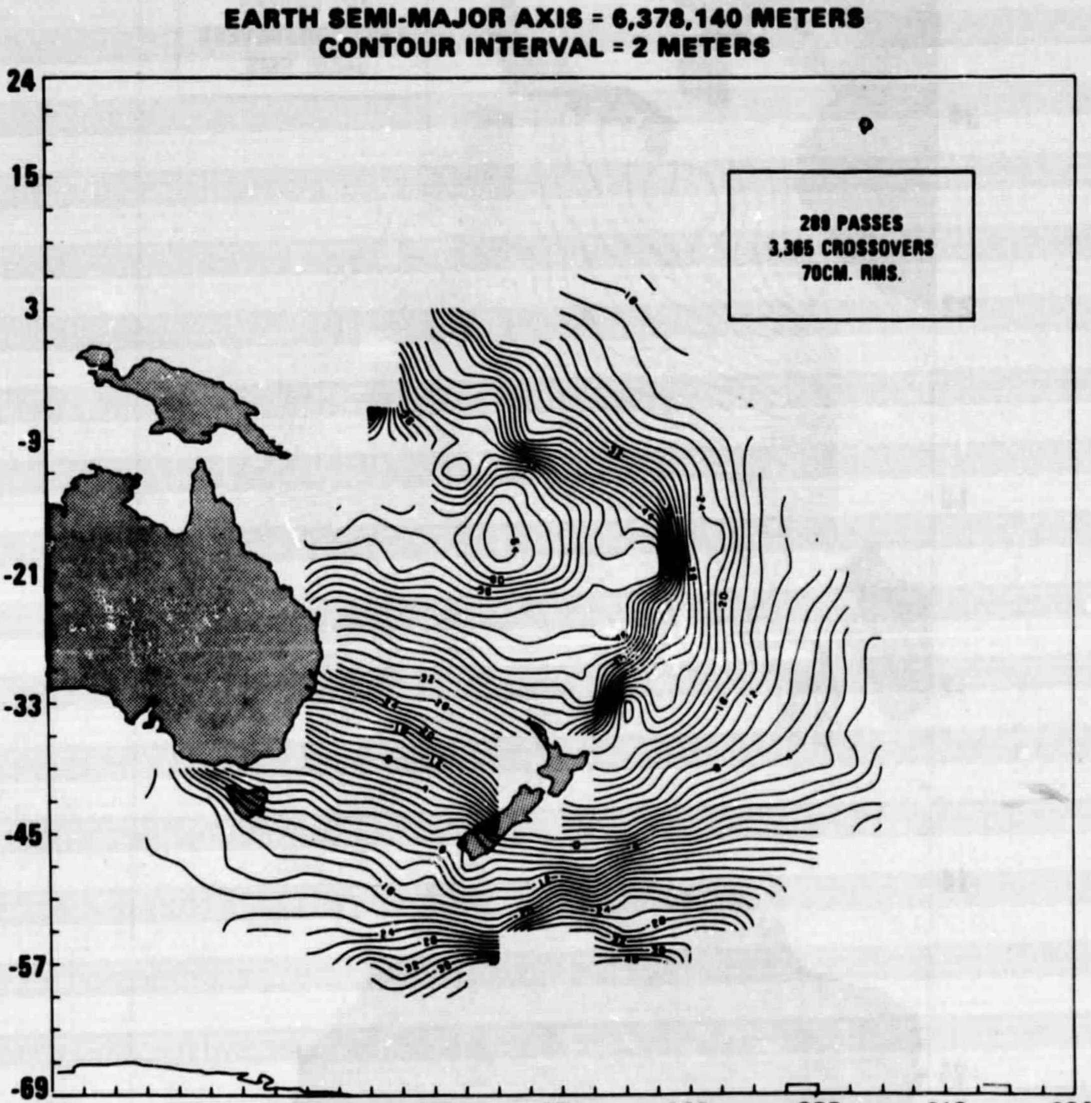


Figure 19. Contour Map of the Ocean Surface Derived from GEOS-3 Altimeter Crossover Data–Southwest Pacific Ocean

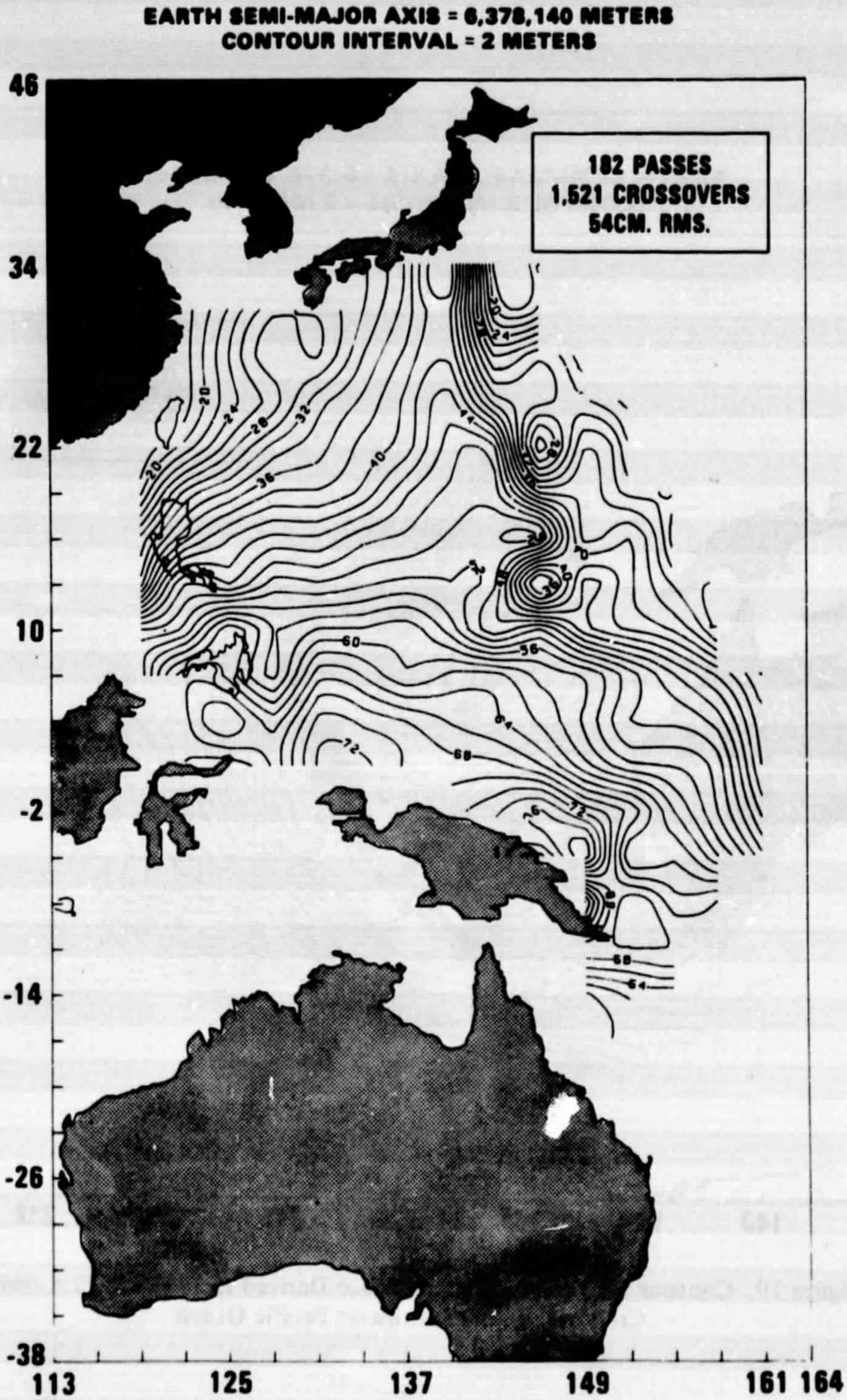


Figure 20. Contour Map of the Ocean Surface Derived from GEOS-3 Altimeter Crossover Data–West Pacific Ocean

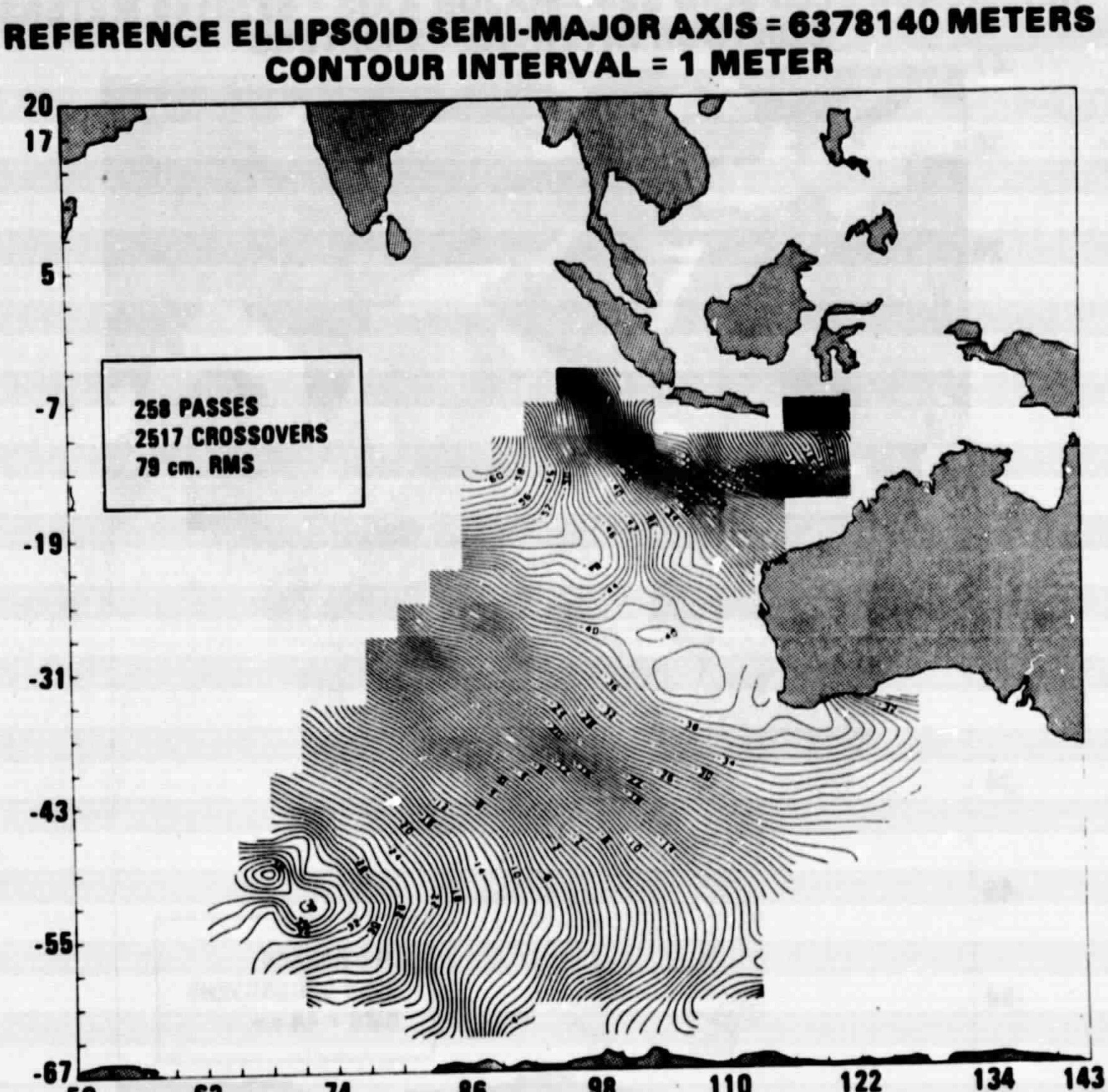


Figure 21. Contour Map of the Ocean Surface Derived from GEOS-3 Altimeter Crossover Data—Southeast Indian Ocean

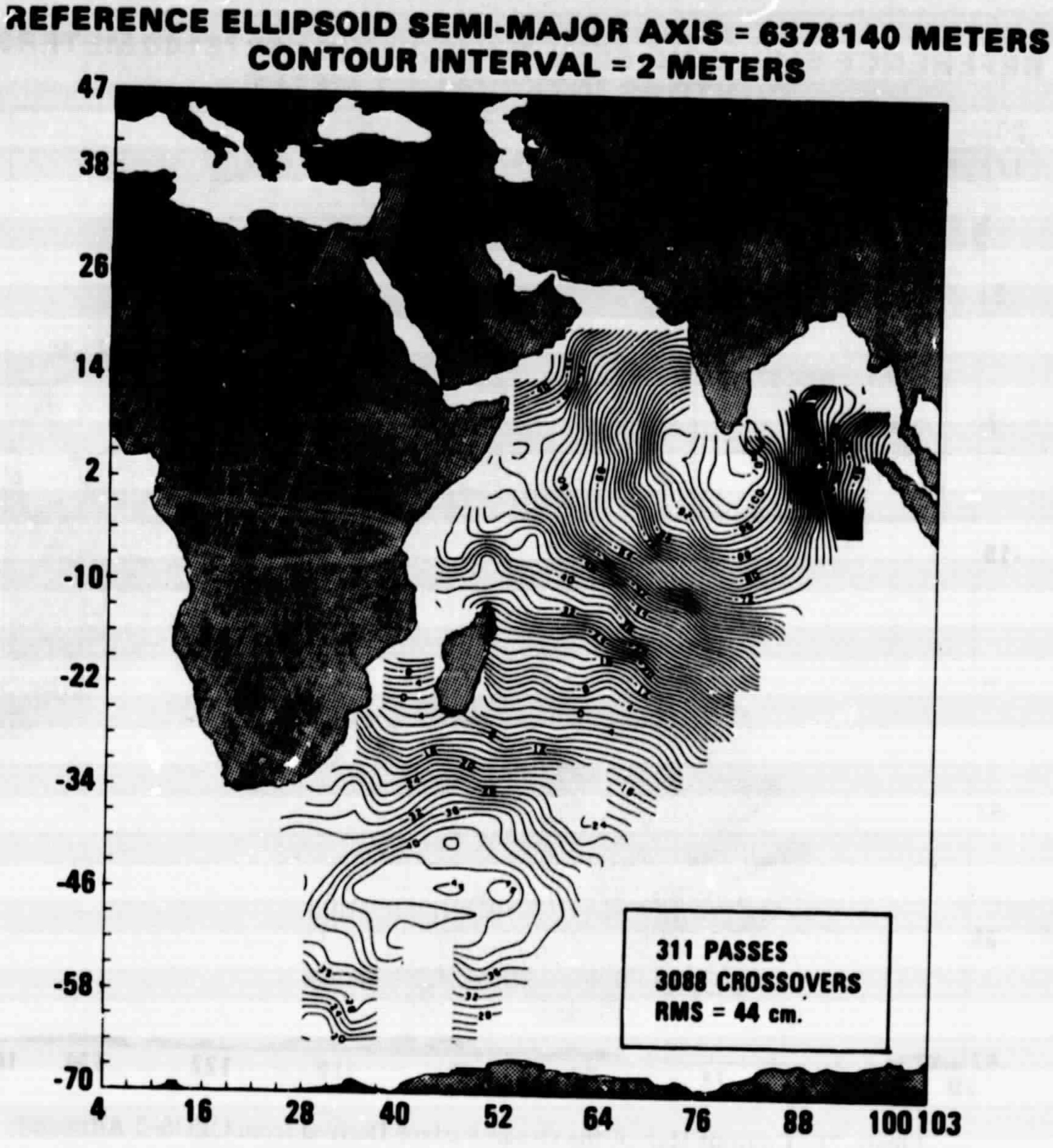


Figure 22. Contour Map of the Ocean Surface Derived from GEOS-3 Altimeter Crossover Data—Western Indian Ocean