NOAA Technical Memorandum NOS NGS-46

GEOSAT ALTIMETER GEOPHYSICAL DATA RECORD

USER HANDBOOK

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Rockville, MD

July 1987

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Ocean Service / Office of Charting and Geodetic Services

Availability

The U.S. Navy altimeter satellite GEOSAT began the unclassified Exact Repeat Mission (ERM) on November 8, 1986. Under agreement with the U.S. Navy and in collaboration with the Johns Hopkins University Applied Physics Laboratory, NOAA has assumed responsibility for generating and distributing the GEOSAT ERM Geophysical Data Records (GDR's). The GEOSAT User Handbook describes how the GDR's are produced, provides information on content and format, and offers guidelines for analysis.

GEOSAT GDR's together with the user handbook are available through NOAA's National Environmental Satellite Data and Information Service at the following addresses:

For Ocean GDR's

National Oceanographic Data Center
User Services Branch
NOAA/NESDIS E/OC21
Washington, DC 20235

Phone: (202) 673-5549 or FTS 673-5549
Electronic Mail: OMNET/MAIL mailbox NODC.WDCA

For land/ice GDR's:

National Geophysical Data Center
NOAA/NESDIS E/GC1
325 Broadway
Boulder, CO 80303

Phone: (303) 497-6128 or FTS 320-6128
Electronic Mail: GTE mailbox [DHASTINGS/NESDIS] TELEMAIL/USA

An order form for puchasing GEOSAT data can be found in appendix A of this handbook. Additional information can be obtained from the authors at the following address:

Geodetic Research and Development Laboratory
National Geodetic Survey
NOAA/NOS N/CG11
Rockville, MD 20852

Phone: (301) 443-8556 or FTS 443-8556
Electronic Mail: OMNET/MAIL mailbox NOAA.GEOSAT

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UNITED STATES DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

National Oceanic and Atmospheric Administration
Anthony J. Calio, Under Secretary

National Ocean Service
Paul M. Wolff, Asst. Administrator

Charting and Geodetic Services
R. Adm. Wesley V. Hull, Director

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THE GEOSAT ALTIMETER MISSION

Background

In March 1985 the U.S. Navy altimeter satellite GEOSAT began generating a new data set with unprecedented spatial and temporal coverage of the global oceans. The satellite (fig. 1), designed and built at the Johns Hopkins University Applied Physics Laboratory in Laurel, MD, carries a radar altimeter that provides a profile of sea level along the satellite groundtrack. Such records enable determination of sea level and its variability, and have application in many areas of geodesy and ocean dynamics. Experience with GEOS-3 and SEASAT in the 1970's demonstrated the enormous potential of altimetry, but neither mission provided a data set that was both long term and global in coverage.

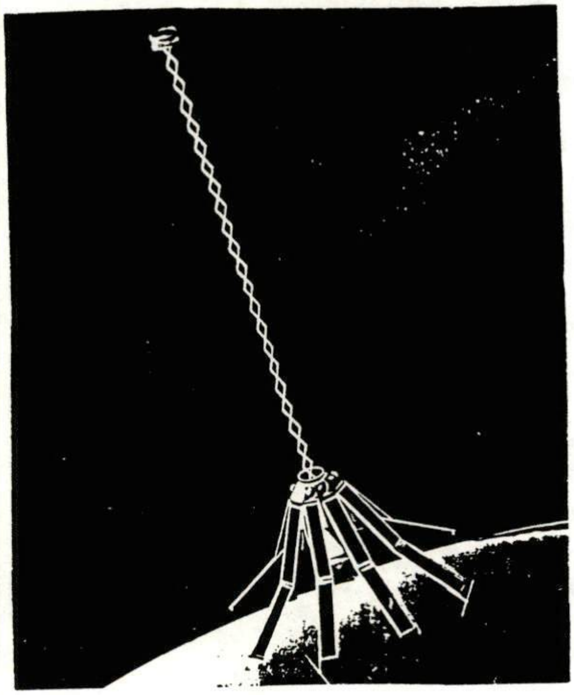

Figure 1.--Artist's conception of GEOSAT in orbit. The gravity gradient boom keeps satellite oriented toward nadir and at a constant aspect to the relative wind. The latter is an important contributor to accurate orbits obtained by the Navy Astronautics Group for GEOSAT.

[1] Now at Johns Hopkins University Applied Physics Laboratory, Laurel, MD.

The Geodetic and Exact Repeat Missions of GEOSAT

As suggested by the acronym GEOSAT (GEOdetic SATellite), the satellite's primary purpose was improvement of the marine gravity field. Because of the value of this information to the U.S. military, the first 18 months of observations are classified. However, the geodetic mission ended September 30, 1986, and on October 1 a series of maneuvers was begun to alter the orbit to produce sea surface profiles within a few kilometers of previously released SEASAT data tracks. This new orbit has a repeat period of about 17 days, and the mission is now referred to as the GEOSAT Exact Repeat Mission (ERM). The ERM officially became operational November 8, 1986.

The ERM groundtrack (fig. 2) is designed to repeat within a 1 km band after 244 revolutions, i.e., 17.05 days. Maneuvers performed approximately once per month maintain the collinearity of the groundtrack to a few hundred meters. The resolution at the equator is approximately 150 km, so an excellent sample of the oceans is obtained. Since the groundtrack for the ERM is very close to previously released SEASAT altimeter data tracks, the new data are unclassified. Under agreement with the U.S. Navy, NOAA/National Ocean Service is producing the ERM Geophysical Data Records (GDR's), with distribution through NOAA's National Oceanographic Data Center (NODC). All spacecraft systems have performed well thus far, and it is anticipated that the ERM will last at least several more years, and possibly until 1992.

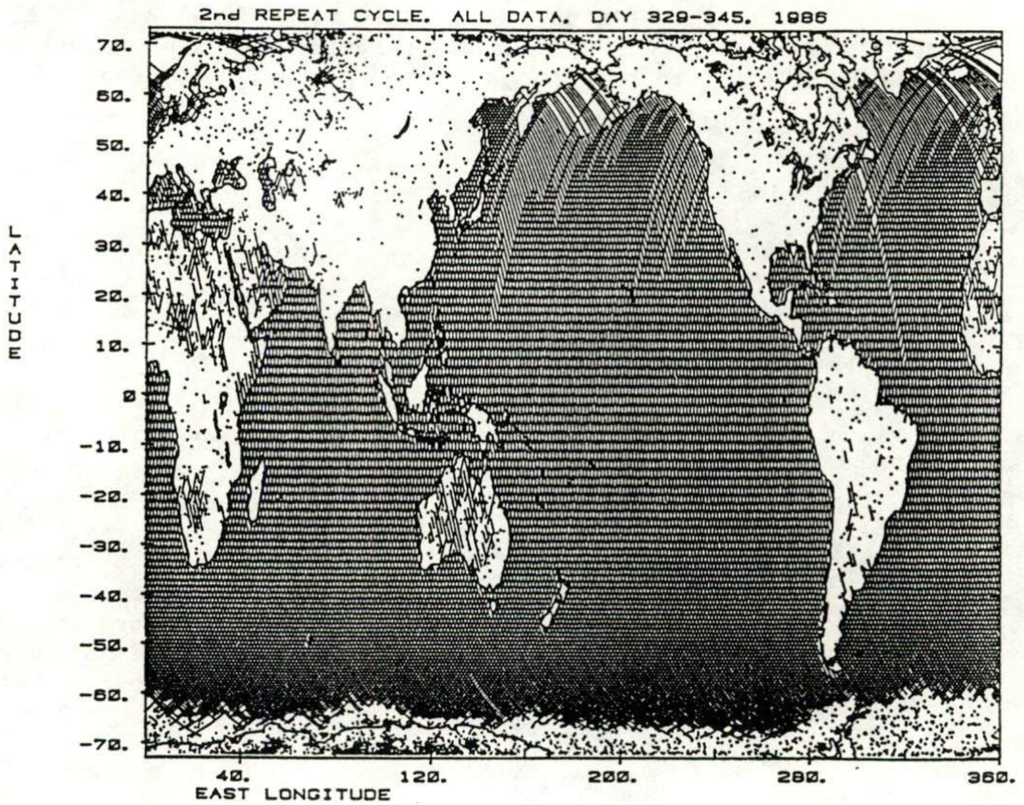

Figure 2.--GEOSAT ERM groundtrack after 1 complete 17-day cycle. Spacing at the equator in approximately 150 km. Data loss in the northern hemisphere is due to large off-nadir attitude excursions.

Ephemeris Computations for GEOSAT

The ephemeris for the GEOSAT ERM is computed by the Navy Astronautics Group (NAG) from Doppler tracking data taken at four sites, three of which are in the continental United States, and one in Hawaii. Tracking station coordinates currently in use have World Geodetic System (WGS) 72 values, and the NASA GEM 10 (Lerch et al. 1979) geopotential model is used for calculation of geopotential perturbations. This system produces radial ephemerides for GEOSAT of approximately 4 m accuracy (rms). This error is almost entirely at a wavelength equal to the orbital circumference, so that determinations of sea level variability at shorter wavelengths can be made successfully.

Ephemerides computed by NAG are in the form of 2-day arcs with 1 day overlapping. The overlap reduces, but does not eliminate, the inevitable discontinuity that occurs at junctions of orbital arcs. In some cases for previous satellites this discontinuity has been dealt with by applying a smoothing algorithm between arcs to give the appearance of continuity. We have chosen not to do this so that investigators will always know what was done to the data. To minimize the effect of the discontinuities of the ephemerides, we have selected the beginning and end of each GDR to occur at maximum latitude which is almost always over land or ice. In addition, the middle 24 hours of each 2-day arc is used because in least squares orbit adjustments the middle of the arc is usually the most accurate.

It is possible that the GEOSAT ERM ephemerides could be improved by a different selection of geodetic parameters. NAG is currently undertaking a study and expects to change to improved procedures in mid-1987. New station coordinates will be used based on Global Positioning System (GPS) ties made by NOAA/National Geodetic Survey to the NASA laser/VLBI (Very Long Baseline Interferometry) global tracking network. The accuracy of these new coordinates will be 10-20 cm, at least an order of magnitude improvement over WGS 72 values. A new geopotential model will also be employed. These and other changes should reduce the NAG ephemeris error by at least one half and will also alleviate somewhat the discontinuities that occur at orbital arc boundaries. The new procedures are expected to be implemented approximately October 1, 1987. If sufficient demand arises, ephemerides will be recomputed from the beginning of the ERM and submitted to NODC for distribution.

GEOPHYSICAL DATA RECORDS - OCEAN

General Description

Geophysical Data Records (GDR's) are produced by combining several different sets of input data, shown schematically in figure 3. Raw altimeter data in the form of Sensor Data Records (SDR's) are first collected at the Johns Hopkins University Applied Physics Laboratory (JHU/APL) ground station in Laurel, MD. These are then transmitted to the NOAA processing facility in Rockville, MD, where they are merged with ephemerides provided by NAG. Corrections are subsequently added to account for solid and fluid tides, and path-length effects due to the troposphere (wet and dry) and ionosphere. Completed GDR's are then sent to NODC in Washington, DC, for distribution. Each GDR covers a period of approximately 24 hours and contains data for either 14 or 15 complete revolutions, beginning and ending as close as possible to maximum latitude (72 degrees north).

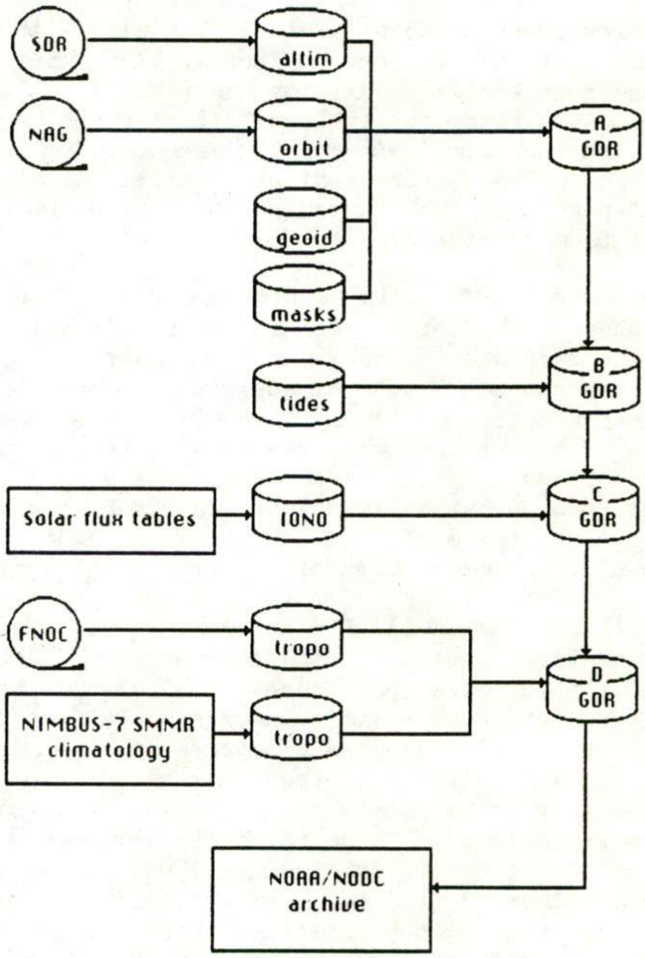

Figure 3.--Flow chart describing production of the GEOSAT Exact Repeat Mission GDR's at NOAA National Ocean Service in Rockville, MD.

GEOSAT GDR's follow to a great degree the form of those prepared for SEASAT by the Jet Propulsion Laboratory, and GEOS-3 by NOAA/NOS. The most significant difference for the user is the inclusion of the full 10 per second data in addition to 1-second averages. This was done for two reasons. First, 1-second averages obliterate real signals in the 10/second data which may be of interest to some investigators. The second and probably more important reason has to do with the problem of interpolating data to compare crossing or collinear data tracks. Since many marine geoidal features are linear (e.g., fracture zones), an interpolation of the data that preserves their inherent precision cannot be made from 1/second records.

The greatest weakness of GEOSAT altimeter data for oceanographic applications arises from a lack of measurement systems onboard the satellite to determine the path-length effects of the ionosphere and wet troposphere. For these corrections we have been forced to resort to models that are based on limited observations. The ionosphere model is a simple global scale version driven by daily values of solar flux. Its accuracy is at the 50 percent level or better, which is adequate now because of the fortunate concurrence of the GEOSAT mission and a solar minimum. Values of the daytime correction are typically ~5 cm at this time. In addition, most of the effect is at long wavelengths. Thus deficiencies of the ionosphere model are not a limiting factor in the use of GEOSAT data.

Two wet troposphere corrections are provided on the ERM GDR's. One is provided by the U.S. Navy Fleet Numerical Oceanographic Center (FNOC) and is derived from a model updated every 12 hours and driven by a large set of observational data. The other correction is a climatological one based on 3 years of NIMBUS-7 SMMR (Scanning Multichannel Microwave Radiometer) observations (Prabhakara et al. 1985). The accuracy of these models is difficult to quantify in a simple manner. Comparisons of along-track SEASAT SMMR data with FNOC values showed that FNOC consistently underestimated the wet troposphere correction (Tapley et al. 1982). The rms difference between SEASAT SMMR and FNOC wet troposphere corrections was estimated to be approximately 6 cm. The NIMBUS-7 SMMR values on the ERM GDR's are monthly means and are estimated to be accurate to 5 cm over the observation period (1979-81) on which the means are computed. This situation probably appears worse than it is. The GEOSAT ERM is primarily a sea level variability mission and so variability of the error of the corrections is the only important factor. In regions where the variability of water vapor is small compared to ocean dynamic signal sought, the correction will be adequate.

Parameter Definition

The GEOSAT GDR's are prepared from Sensor Data Records (SDR's) that have been certified at JHU/APL to contain no classified information. These SDR's are described in detail in the Interface Control Document (JHU/APL 1985) which will be provided to GEOSAT users together with this NOAA GEOSAT GDR User Handbook. The exact description of the GDR parameters is given below. Table 1 briefly summarizes the fields contained in the GDR. The data are output as binary 2's complement integer fields either 4 or 2 bytes in length. The leftmost bit is referred to as either bit 31 or bit 15 and is the sign bit; the rightmost bit is referred to as bit 0 and is the units bit. The record length is 78 bytes and some multiple of 78 bytes is the block length of the tape. Thus, the leftmost of the 624 bits per record is bit 31 of the time in seconds from the start of 1985, and the rightmost of the 624 bits is bit 0 of the attitude. Certain machines store their binary integers in other than strictly left to right (31-0) form or use the 1's complement representation of integer data; the user must know if his or her machine does this in order to correctly load the bits into memory.

Table 1.--Geophysical data record contents

ITEM	PARAMETER	UNITS	RANGE	BYTES
1	UTC	SEC	0 to 2E31	4
2	UTC(cont'd)	MICRO SEC	0 to 1E6	4
3	LATITUDE	MICRO DEG	+/- 7.21E7	4
4	LONGITUDE	MICRO DEG	0 to 3.60E8	4
5	ORBIT	MM	7E8 to 9E8	4
6	H	CM	+/- 32766	2
7	SIGMA_H	CM	0 to 32766	2
8	GEOID	CM	+/- 1.5E5	2
9	H(1)	CM	+/- 32766	2
10	H(2)	CM	+/- 32766	2
11	H(3)	CM	+/- 32766	2
12	H(4)	CM	+/- 32766	2
13	H(5)	CM	+/- 32766	2
14	H(6)	CM	+/- 32766	2
15	H(7)	CM	+/- 32766	2
16	H(8)	CM	+/- 32766	2
17	H(9)	CM	+/- 32766	2
18	H(10)	CM	+/- 32766	2
19	SWH	CM	0 to 2E3	2
20	SIGMA_SWH	CM	0 to 2E3	2
21	SIGMA_NAUGHT	.01 DB	0 to 6.4E3	2
22	AGC	.01 DB	0 to 6.4E3	2
23	SIGMA_AGC	.01 DB	0 to 6.4E3	2
24	FLAGS			2
25	H OFFSET	M	0 to 5.0E4	2
26	SOLID TIDE	MM	+/- 1000	2
27	OCEAN TIDE	MM	+/- 10000	2
28	WET(FNOC)	MM	0 to -1000	2
29	WET(SMMR)	MM	0 to -1000	2
30	DRY(FNOC)	MM	-2000 to -3000	2
31	IONO(GPS)	MM	0 to -500	2
32	dh(SWH|ATT)	MM	+/- 9999	2
33	dh(FM)	MM	+/- 999	2
34	ATTITUDE	.01 DEG	0 to 200	2
			TOTAL NUMBER OF BYTES	78

Item No.	Parameter	Definition
1	UTC	Universal Time Coordinated in seconds since the beginning of 1985. UTC = 0 refers to January 1, 1985, 00 hours, 00 minutes, 00 seconds
2	UTC (cont'd)	Time continued in microseconds
3	LATITUDE	North latitude in microdegrees (negative for south latitude)
4	LONGITUDE	East longitude in microdegrees relative to Greenwich meridian
5	ORBIT	Satellite height in millimeters above the reference ellipsoid, where the ellipsiod is defined by a = 6378.137 km f = 1/298.257223563 The satellite orbit is computed by the Navy Astronautics Group (NAG), Point Mugu, CA, using Doppler tracking from three stations in the continental United States and one in Hawaii. The GEM 10 geoid model is used in these computations, and ephemerides are provided relative to the WGS 72 coordinate system. Orbit determination software was developed by JHU/APL for the Navy navigation satellite system (JHU/APL 1981). Orbits are computed for 2-day arcs beginning approximately 1200 UTC, with 1-day overlap of consecutive orbit computations. Ephemeris is provided at 1-minute intervals and is evaluated at approximately 0.1-second intervals with a 9-point Lagrangian interpolator for use with 10/second altimeter range measurements.
6	H	One-second average sea surface height in centimeters above the reference ellipsoid. (See figs. 4 and 5.) H = ORBIT/10 - ALTIMETER where ORBIT = satellite height in millimeters above the ellipsoid

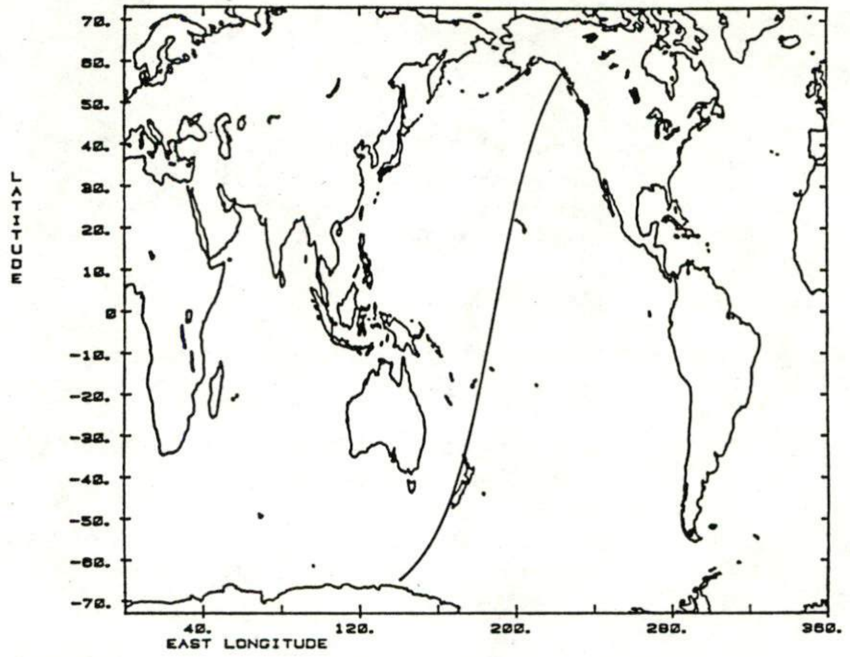

Figure 4.--GEOSAT groundtrack for first descending pass on Nov. 25, 1986. Profiles of various parameters along this track are shown in subsequent figures.

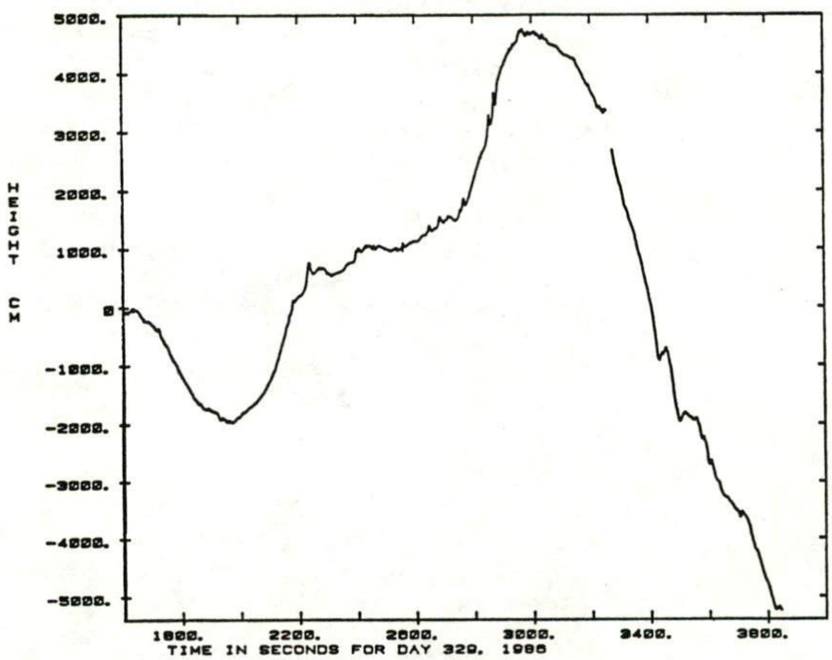

Figure 5.--One-second average sea surface heights (H) above reference ellipsoid for descending pass shown in figure 4.

ALTIMETER = measured height in centimeters between the satellite and the sea surface, after correction for FM crosstalk, spacecraft center-of-gravity, prelaunch calibration, and attitude/SWH bias (JHU/APL 1985: p. 73)

The 1-second average height value H is derived from the 10 per second heights (items 9-18). The data compression algorithm is a linear fit with iterative outlier rejection. A straight line is fit by least squares to the 10/second data, and the largest approximately standardized residual is tested against a tau distribution at the 95 percent confidence level (Pope 1976). Failure of the test causes elimination of the point associated with that single largest residual, and causes recomputation of the line fit with the remaining points. Convergence is obtained when the largest residual passes the tau test. At convergence, H is evaluated at the central time of the 1-second interval (UTC above). As many as four iterations may be performed to achieve convergence; at least six non-rejected points are required to compute H and SIGMA H. If less than six good points are available, H and SIGMA H are set = 32767.

NOTE: H is NOT corrected for environmental effects (wet and dry troposphere, ionosphere), and tides. Environmental corrections may be incorporated by the formula:

H (corrected) = H - SOLID TIDE/10
- OCEAN TIDE/10
- WET(FNOC or SMMR)/10
- DRY(FNOC)/10
- IONOSPHERE/10

7	SIGMA H	Standard deviation in centimeters from a linear fit to the 10/second sea height values used in computing H. (See figs. 6 and 7.) Only non-rejected values are used to compute SIGMA H and a minimum of six good points is required.
8	GEOID	Geoid height in centimeters above GRS 80 ellipsoid. (See fig. 8.) Value computed with bilinear interpolation using 1 degree geoid height estimates computed from Rapp (1978).

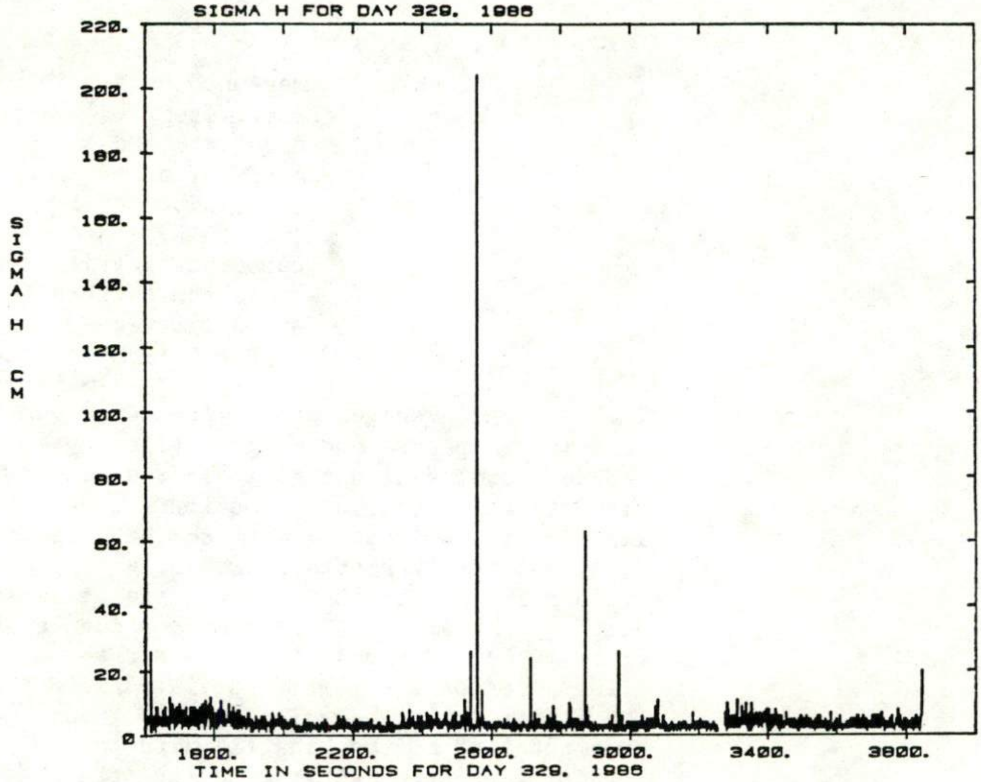

Figure 6.--Standard deviation of 1-second H for pass shown in figure 5.

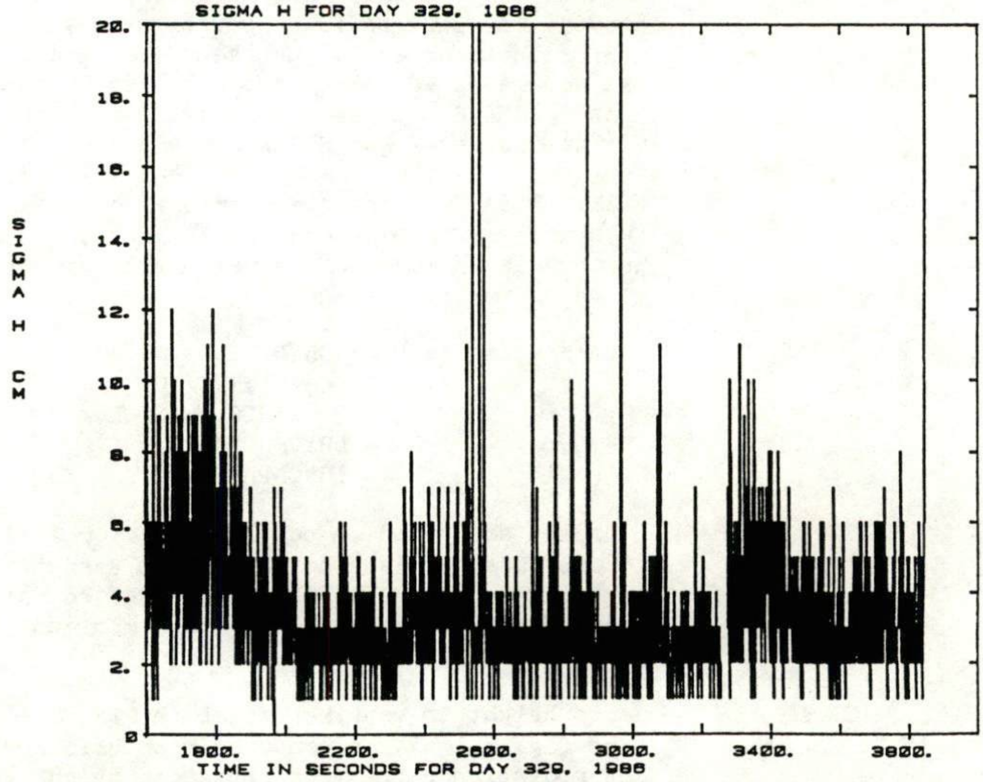

Figure 7.--An expanded view of figure 6. Typical value of sigma H is about 5 cm.

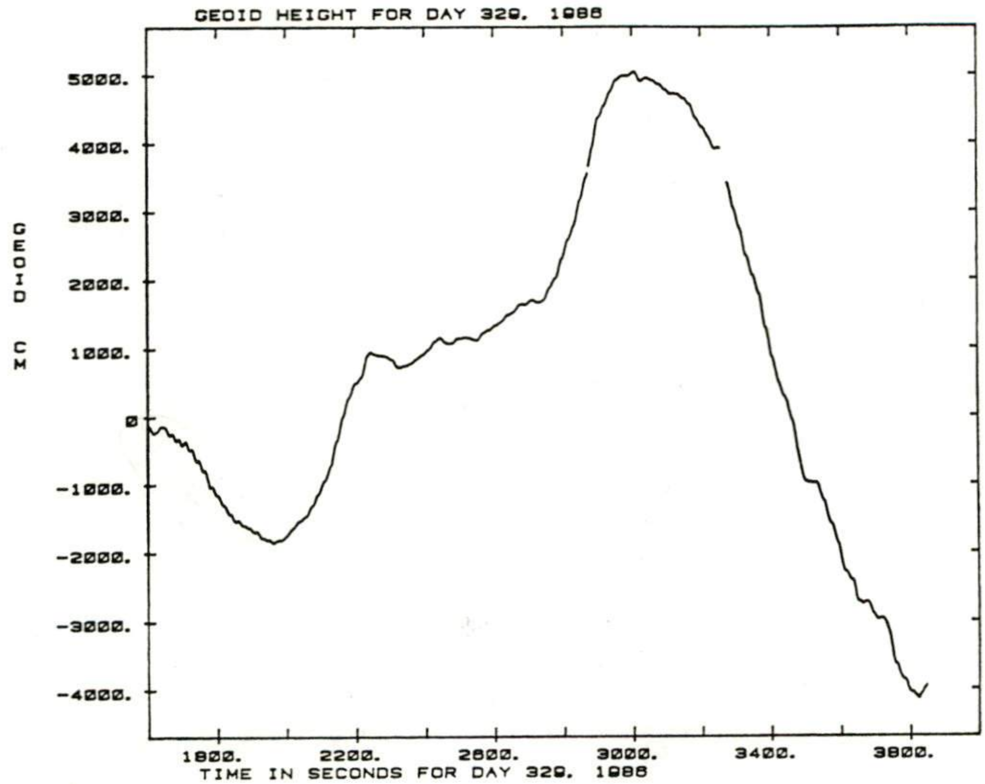

Figure 8.--Geoid height along groundtrack shown in figure 4. Note close agreement (a few meters) of geoid height with H in figure 5.

9-18	H(1)-H(10)	Sea height values in centimeters at 10 per second rate and used to form H. (See fig. 9.) To time tag the 10 height values, use: time(i) = time of record + .97992165(i/10. - .55), i = 1,2,...,10
19	SWH	Significant wave height in centimeters, determined onboard the spacecraft at the rate of 10 per second. (See fig. 10.) SWH is an "average" 1-second value determined from the 10/second data by the method described in item 6. A correction has been applied for attitude/SWH bias (JHU/APL 1985: p. 73).
20	SIGMA SWH	Standard deviation in centimeters of the 10 per second wave height values used in computing SWH. (See fig. 11.) Only non-rejected values are used to compute SIGMA SWH and a minimum of six good points is required.

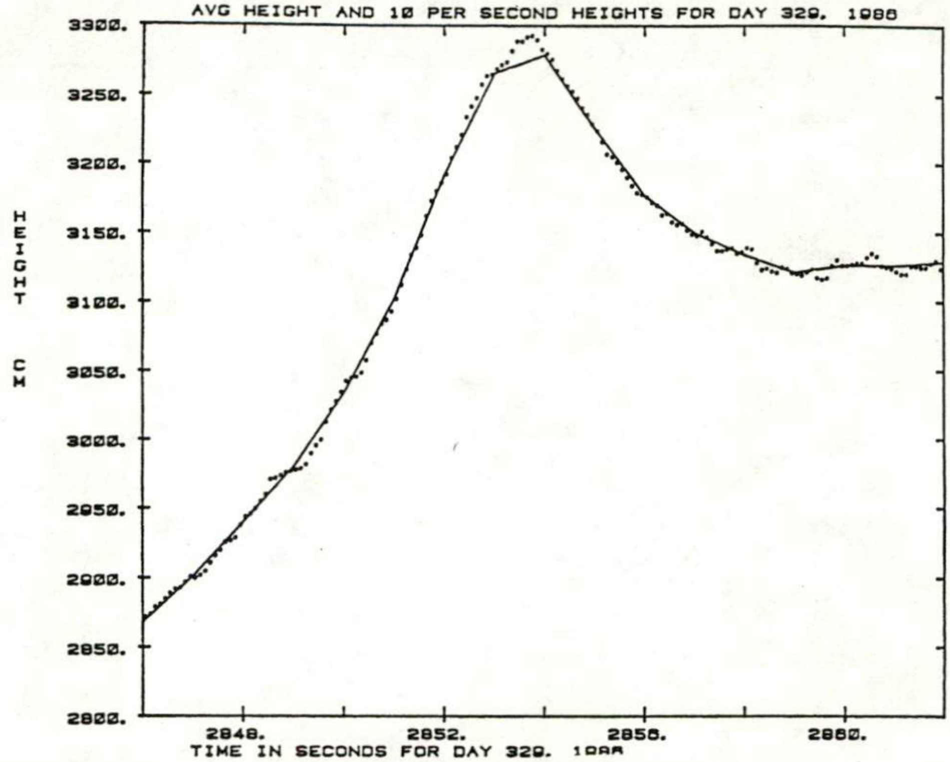

Figure 9.--Sea heights plotted at full 10/second rate for portion of profile in figure 5, with 1-second average values of H superimposed.

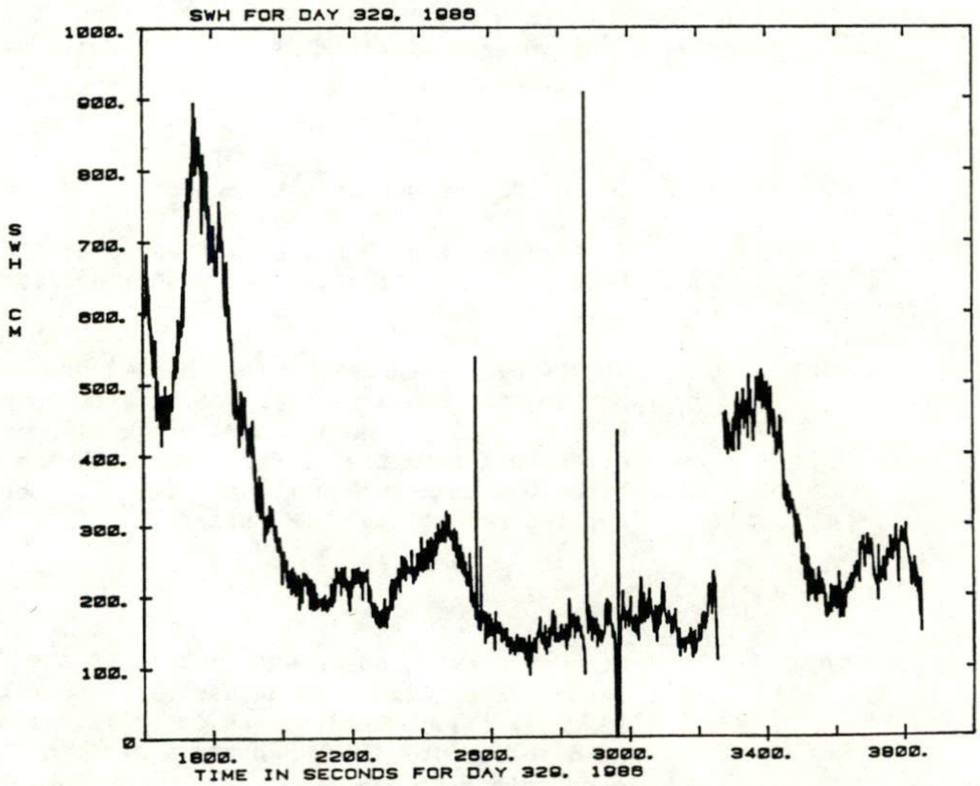

Figure 10.--Significant wave height (SWH) along track shown in figure 4.

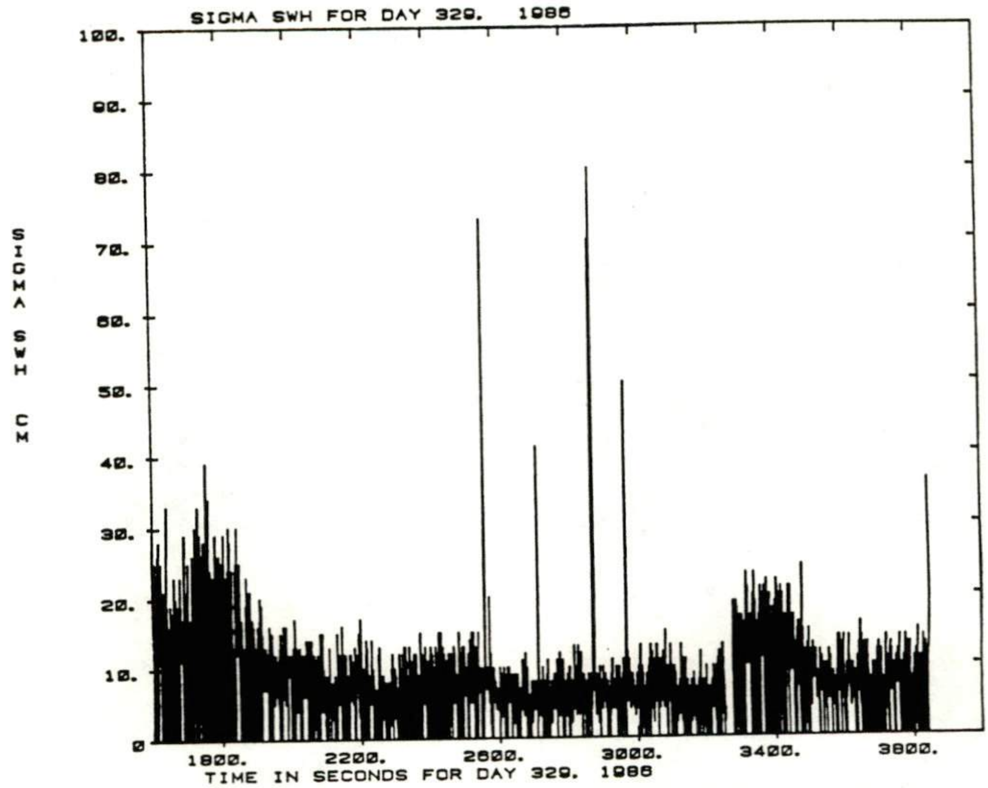

Figure 11.--Sigma SWH corresponding to profile in figure 10.
Typical value is 10 cm.

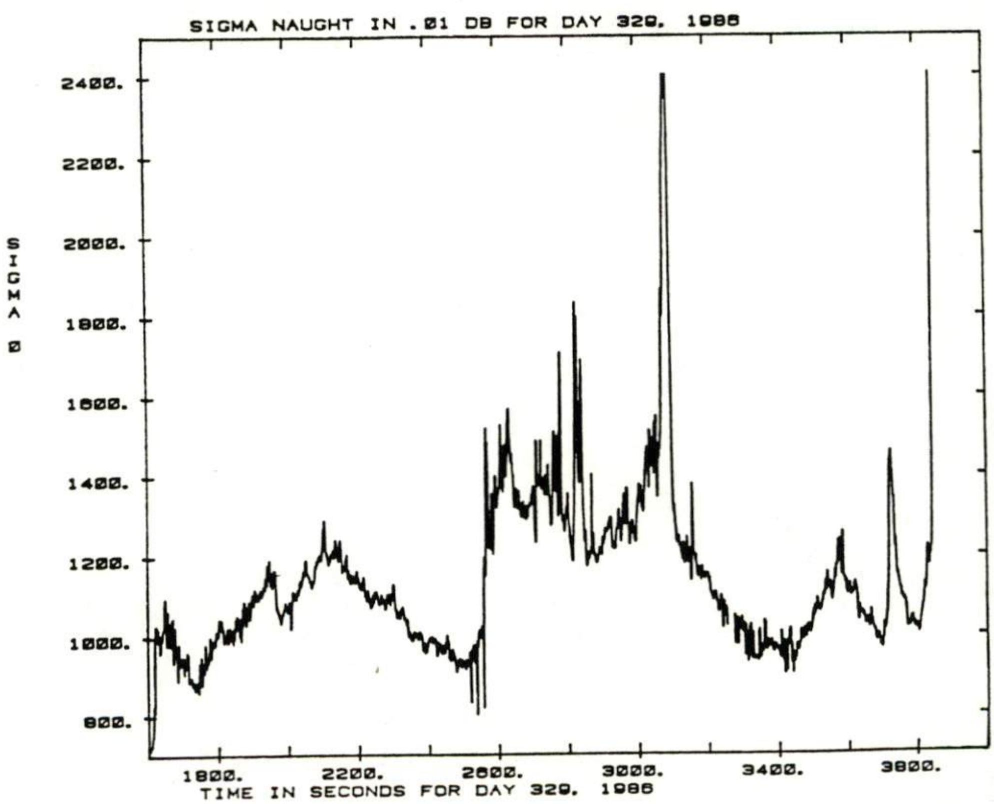

Figure 12.--Sigma naught along track in figure 4.

21	SIGMA NAUGHT	Backscatter coefficient in 0.01 db computed from AGC applying corrections for satellite height, receiver temperature, attitude/SWH effect, onboard calibration, and prelaunch calibration (JHU/APL 1985: p. 73). (See fig. 12.)
22	AGC	Automatic gain control in 0.01 db, determined onboard the spacecraft at a rate of 10 per second. (See fig. 13.) This parameter indicates signal strength at the altimeter receiver. AGC is an "average" 1-second value determined from the 10/second data by the method described in item 6.
23	SIGMA AGC	Standard deviation in 0.01 db of the 10 per second automatic gain control values used in computing AGC. (See fig. 14.) Only non-rejected values are used to compute SIGMA AGC and a minimum of six good points is required.
24	FLAGS	Flag bits 0-15, right to left

0 = 1	if over water based on a 1/12 degree mask (= 0 if over land)
1 = 1	if over water > approx. 2000 m depth
2 = 1	if either dh(SWH/ATT) or dh(FM) out of normal range
3 = 1	if any of the 10/second heights set to 32767 cm
4 = 1	if VATT is extrapolated > 4 minutes (for explanation of VATT, a parameter used to compute ATT, see JHU/APL 1985: pp. 23-24)
5 = 1	if VATT estimated (value not available)
6 = 1	if VATT estimate used less than 60 raw samples
7 = 0	not used
8	checksum (internal NOAA use)
9	checksum
10	checksum
11	checksum
12 = 1	if FNOC interpolation > 12 hours
13 = 1	if solar flux value out of range for the ionosphere model
14 = 0	not used
15 = 0	not used

25	H OFFSET	Offset in meters required for all heights flagged as being over land (zero flag bit = 0). H and H(1)-H(10) are stored in 2-byte fields and can have maximum values of only 32,767 cm. While this is sufficient for all ocean heights, land and ice sheet heights would often be out of range. H OFFSET is a bias equal to the average of the minimum and maximum 10/second height values. This bias has been subtracted from each of the land heights H and H(1)-H(10). Thus to recover heights

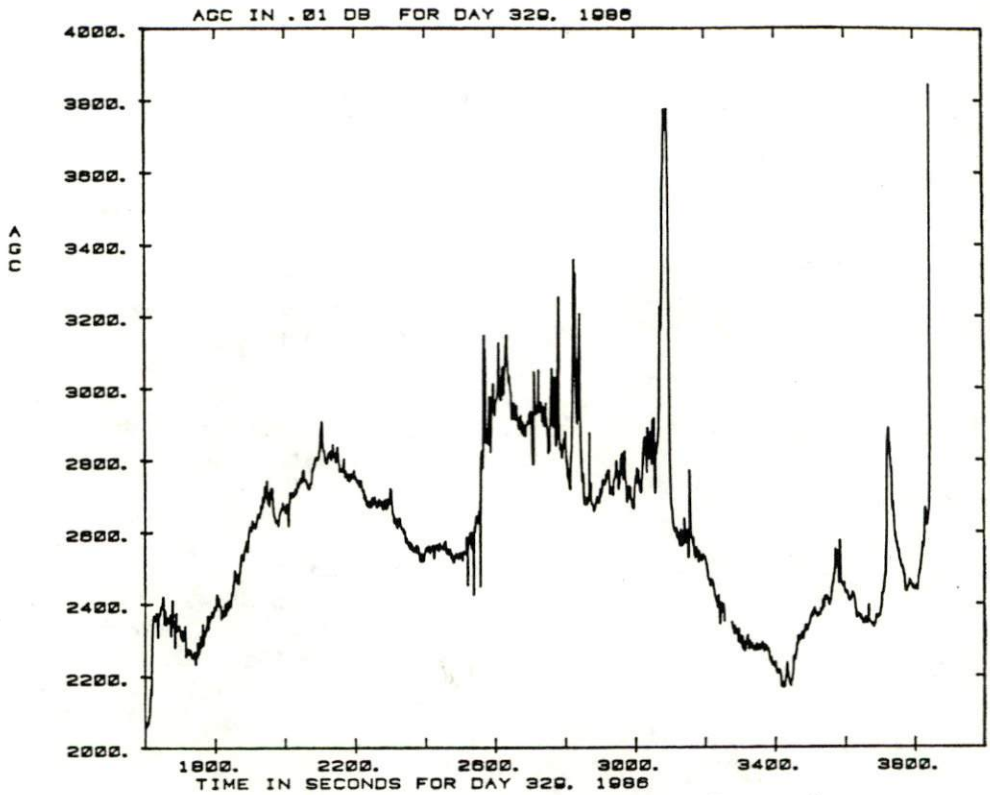

Figure 13.--AGC along track in figure 4.

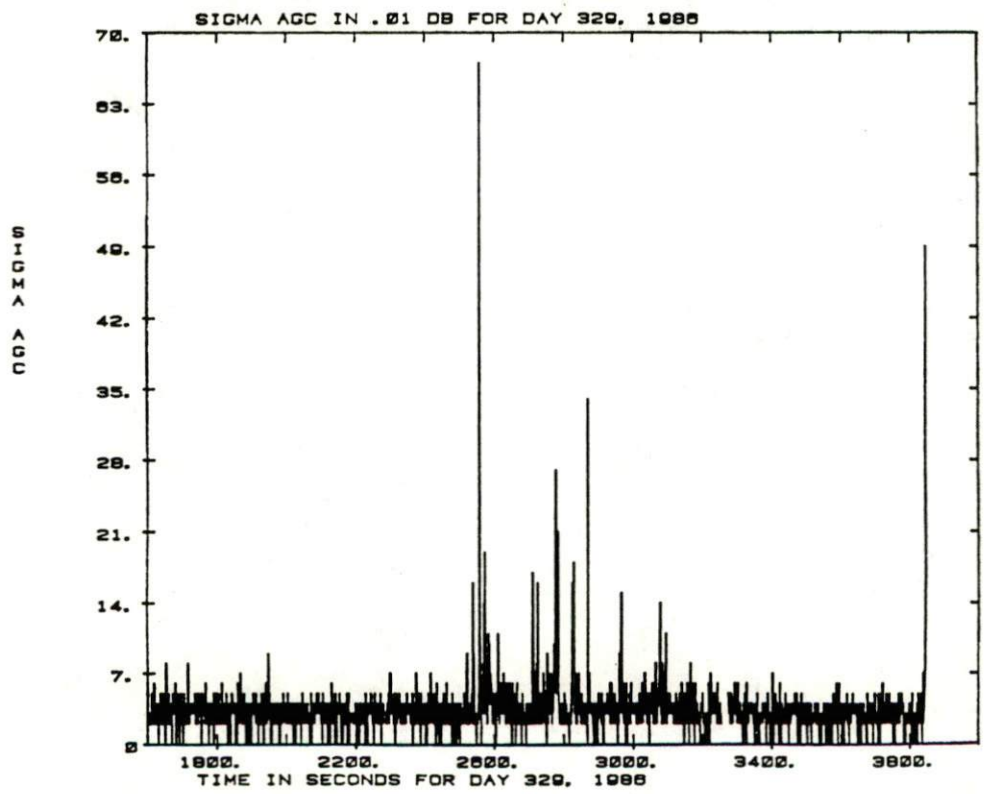

Figure 14.--Standard deviation of automatic gain control (sigma AGC) corresponding to the profile in figure 12. Typical value is 0.04 db.

over land, H OFFSET must be added to all H values for which the land flag = 0

H (corrected) = H + (H OFFSET)*(100)

NOTE: H OFFSET = 0 for altimeter heights over water

26 SOLID TIDE — Solid earth tide correction in millimeters to H. (See fig. 15.) Based on Cartwright and Tayler (1971) and Cartwright and Edden (1973). The solid tide height is extrapolated at 1-second intervals from computations of the tide generating potential and its gradient at 30-second intervals along the satellite groundtrack.

27 OCEAN TIDE — Surface ocean tide correction in millimeters to H. (See fig. 16.) Based on Schwiderski (1980). The surface tide height is interpolated along the satellite track at 1-second intervals from a 1 degree global grid of 11 tidal components (M2, S2, K1, O1, N2, P1, K2, Q1, MF, MM, SSA).

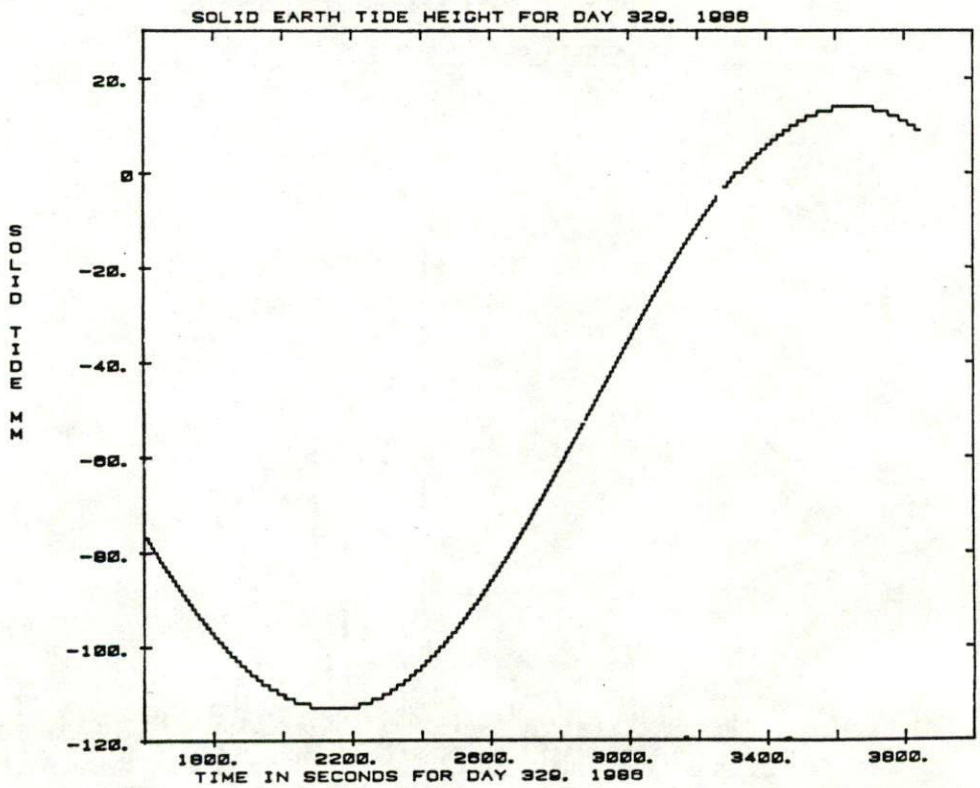

Figure 15.--Solid earth tide correction computed from the model of Cartwright and Tayler (1971) along track in figure 4.

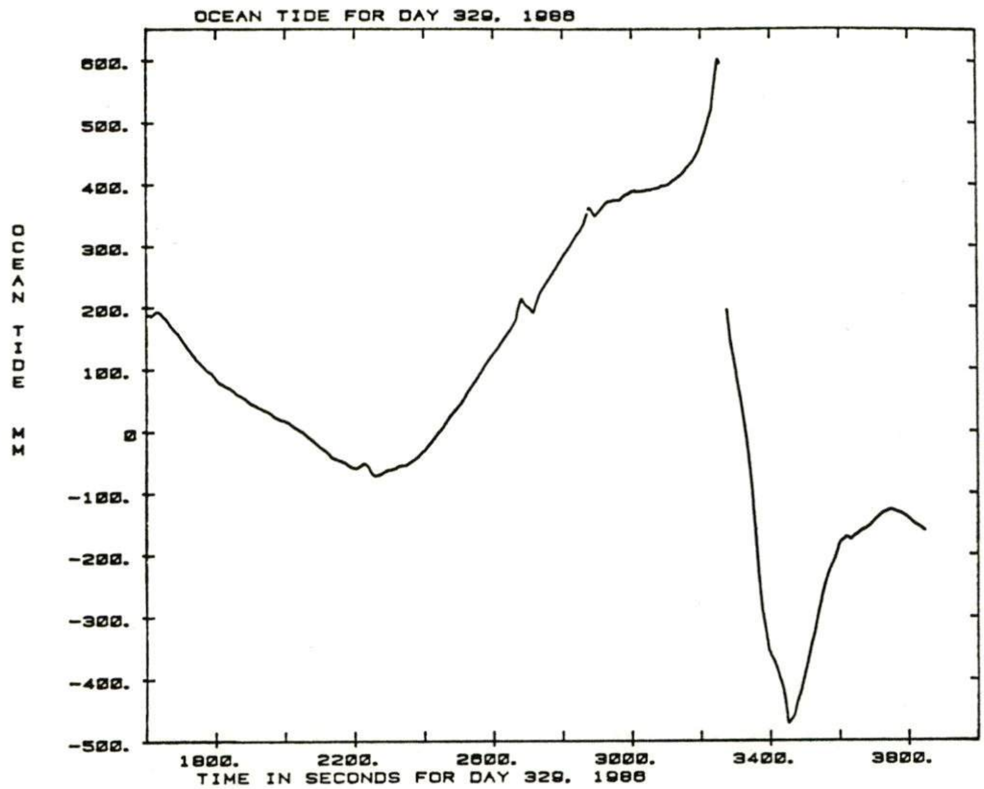

Figure 16.--Ocean tide correction computed from the 11-component Schwiderski (1978) model along track in figure 4.

28	WET(FNOC)	Wet troposphere correction in millimeters to H. (See fig. 17.) This correction compensates for the altimeter travel time delay caused by water vapor in the troposphere. Based on Saastamoinen (1972) and Tapley et al. (1982). Surface values of air temperature and water vapor pressure are interpolated along the satellite track at 1-second intervals from the Fleet Numerical Oceanographic Center (FNOC) NOGAPS model output. (FNOC data are provided in the form of a 2.5 degree global grid at 12-hour intervals.) The wet troposphere correction is then computed using:

$$WET(FNOC) = -2.277 * (0.05 + (1255/(T + 273.16))) * e$$

where:
T = surface atmospheric temperature in degree C
e = surface water vapor pressure in mbar

29	WET(SMMR)	Auxiliary wet troposphere correction in millimeters to H. (See fig. 18.) This correction may be used in lieu of WET(FNOC) correction to compensate for altimeter travel time delay caused by water vapor in the troposphere. Based on Prabhakara et al.

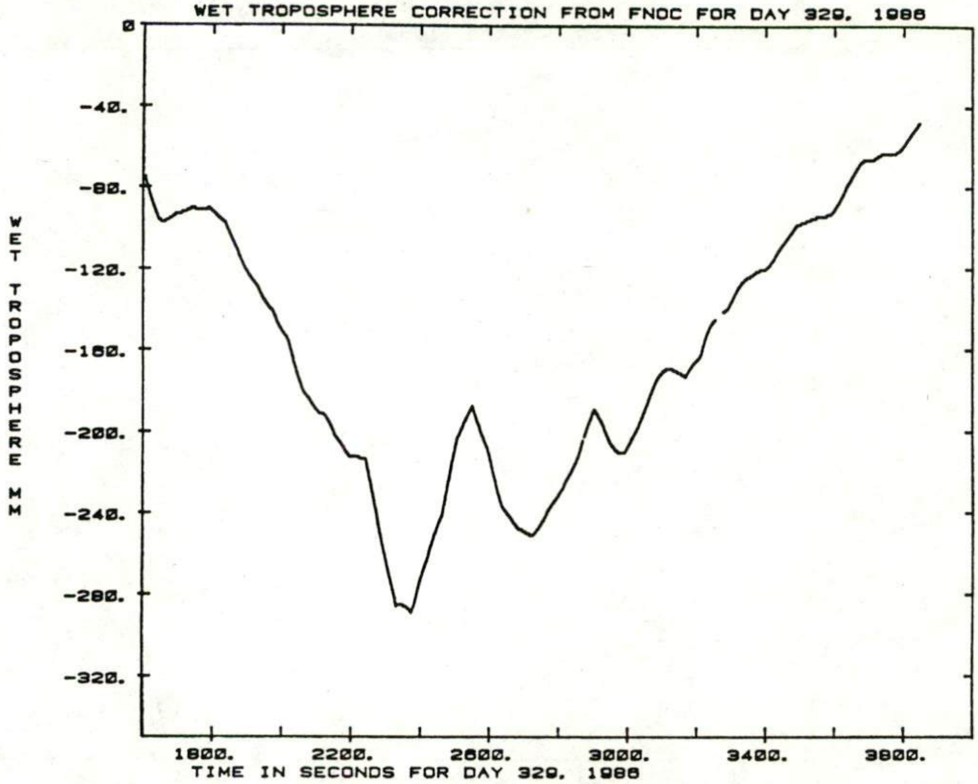

Figure 17.--Wet troposphere correction along track in figure 4 derived from FNOC model.

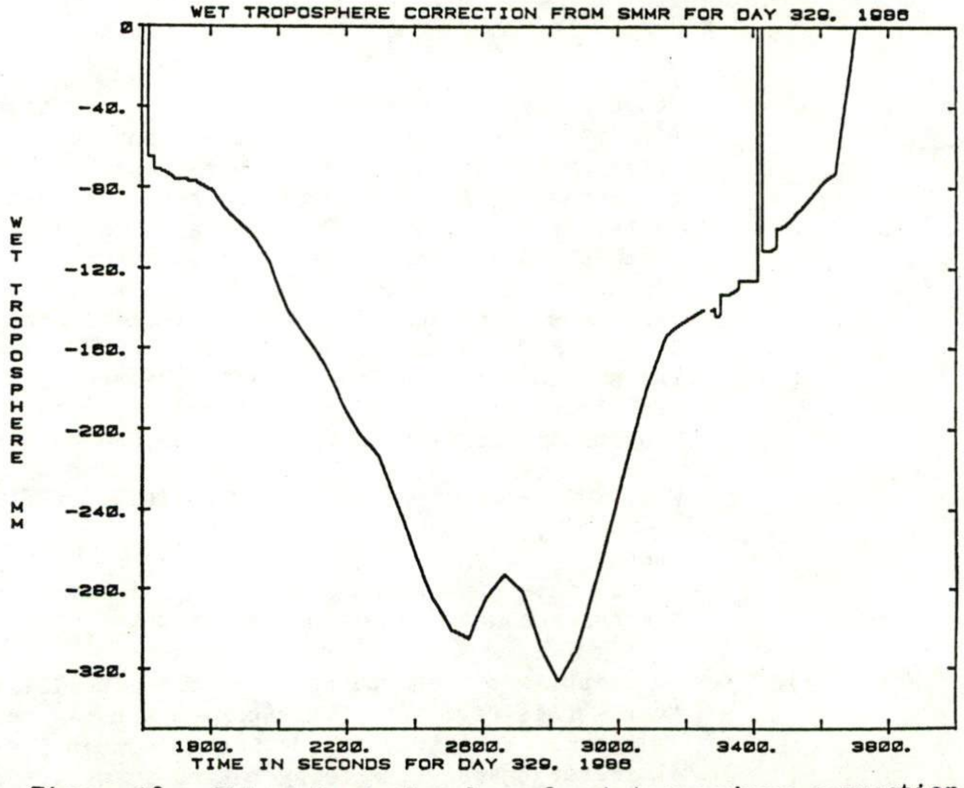

Figure 18.--Climatological value of wet troposphere correction derived from 3 years of NIMBUS-7 SMMR data along track in figure 4.

(1985) and Tapley et al. (1982). Values of vertically integrated atmospheric water vapor are interpolated along the satellite track at 1-second intevals from a climatic monthly mean NIMBUS 7 SMMR data set prepared by C. Prabhakara. (The SMMR data set is in the form of a 3 degree latitude by 5 degree longitude global grid of monthly averages for the years 1979-81). The wet correction is then computed using:

WET(SMMR) = -6.36 * W

where: W = vertically integrated atmospheric water vapor in gm/cm**2

30 DRY(FNOC) Dry troposphere correction in millimeters to H. (See fig. 19.) This correction compensates for the altimeter travel time delay caused by air molecules in the troposphere. Based on Saastamoinen (1972). Values along the satellite track are interpolated at 1-second intervals from the Fleet Numerical Oceanographic Center (FNOC) NOGAPS model output. (FNOC data are provided in the form of a 2.5 degree global grid at 12-hour intervals.) The dry correction is then computed using:

DRY(FNOC) = -2.277*P*(1 + (0.0026 * cos(2 * LATITUDE)))

where: P = surface atmospheric pressure in mbar

NOTE REGARDING INVERSE BAROMETER CORRECTION:
The ocean rises and falls with changes in barometric pressure. However the time scale on which the ocean responds is not well understood. Consequently, this correction is not provided on the GDR. However, one can compute an instantaneous correction using as input the surface atmospheric pressure which is available indirectly via the DRY(FNOC) correction:

P = DRY(FNOC) / (-2.277)(1 + (0.0026 * cos(2 * LATITUDE)))

where: P = surface atmospheric pressure in mbar.

The inverse barometer correction in millimeters is then:

INV BARO = -9.948 * (P - 1013.3)

To apply this correction, it should be subtracted from altimeter sea height, H.

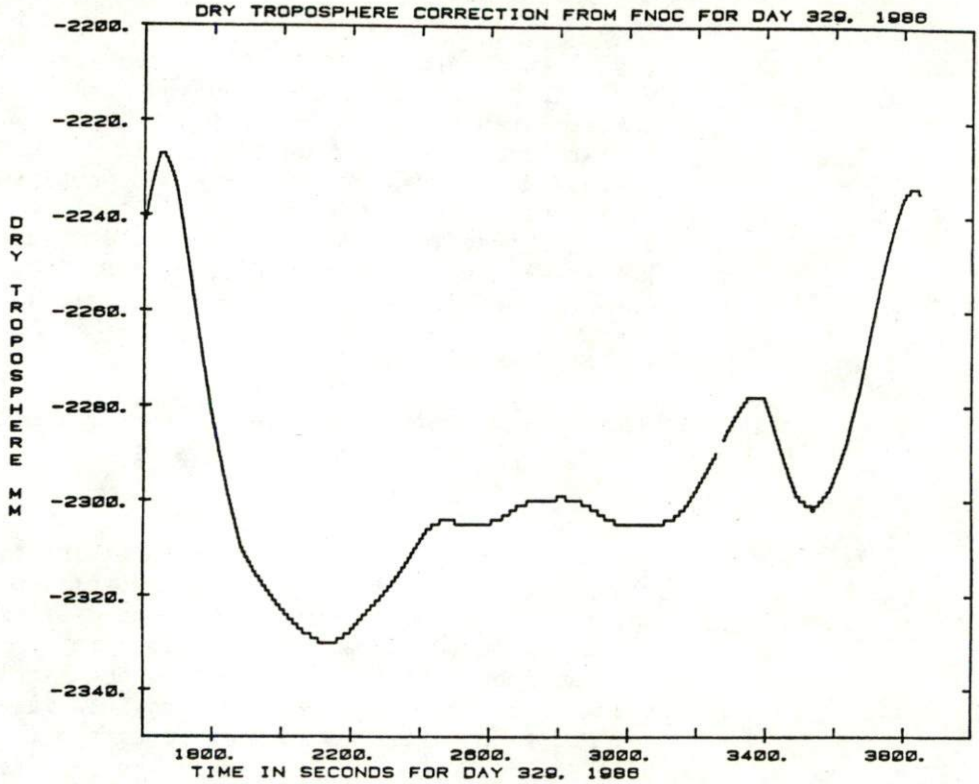

Figure 19.--Dry troposphere correction from FNOC model along track in figure 4.

31	IONO(GPS)	Ionosphere correction in millimeters to altimeter suface height. (See fig. 20.) Based on the Global Positioning System (GPS) climatic ionosphere model. This correction compensates for the altimeter travel time delay caused by free electrons in the ionosphere. The model is estimated to be accurate at the 50 percent level.
32	dh(SWH/ATT)	Height bias in millimeters resulting from a combination of SWH and ATTITUDE. This correction has been applied to values of H and H(1)-H(10) given above. NOTE: dh(SWH/ATT) is not the "sea state", or "EM" bias correction, which has not yet been determined for GEOSAT.
33	dh(FM)	Height bias in millimeters resulting from linear compression of the altimeter pulse. The correction is a function of the compression ratio and the pulse bandwidth (Doppler shift appears as a range shift.) This correction has been applied to values of H and H(1)-H(10) given above.
34	ATTITUDE	Spacecraft off-nadir orientation angle in 0.01 degrees estimated by ground processing of the return waveform trailing edge.

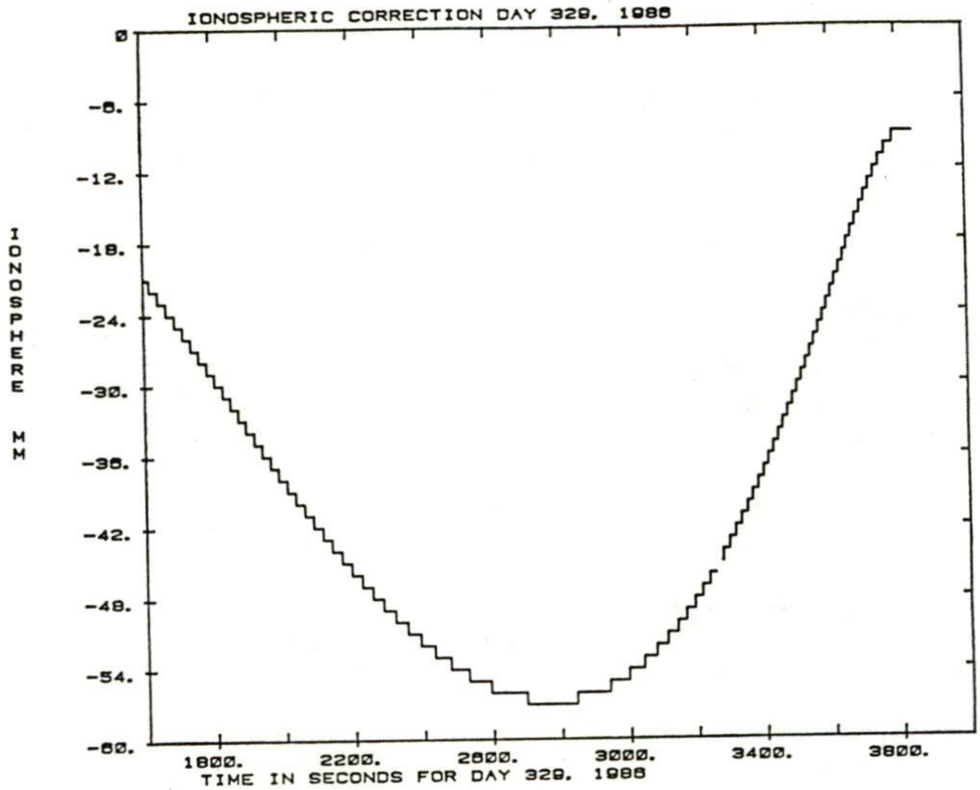

Figure 20.--Ionosphere correction along track in figure 4 computed from model developed at JHU/APL.

GEOPHYSICAL DATA RECORDS - LAND AND ICE

During production of the ocean GDR's editing is performed based on flags provided in the SDR's. This results in elimination of approximately 35,000 1-second points per day, mostly over land and ice. Some of these discarded records contain useful information, especially when combined with corresponding records from the GEOSAT waveform data records (WDR's). In order to create a comprehensive archive of the GEOSAT data, these discarded records are collected in separate land/ice GDR's. These consist of <u>all</u> records over land (regardless of data quality) plus all records over water which failed one of the seven tests summarized on page 22.

Structure of the land/ice GDR's is the same as the ocean GDR's, but additional information is provided in the flag field to indicate which, if any, of the data quality tests were failed. Changes to the GDR flags are provided below:

Bit location	Definition for flag set = 1	Value on ocean GDR's
7	LMax/4 < AGC	0
8	DHa > TDH	0
9	Detect flag not set	1
10	ACQ TC flag not set	0
11	ACQ flag not set	0
15	Record failed one or more of the above flags	0

DATA ANALYSIS CONSIDERATIONS

GEOSAT ERM data contain an enormous amount of information, but just as in the case of GEOS-3 and SEASAT, great care is required to realize an accurate rendering. In this section we provide additional information on selected aspects of the GEOSAT data that may be useful to investigators.

Sensor Data Record Quality Flags

The GEOSAT SDR's contain one record for every 0.98 seconds in the day regardless of data quality or content. Of these 88,000 records per day, only about 53,000 are passed to the final GDR. Data are edited based on SDR flags in order to remove bad points. Checks are made on the following SDR flags. (See JHU/APL 1985, for more information on these flags.)

Flag	Typical number of SDR records failing per day
Unusable flagword	10
Not track mode 1, 2, 3, or 4	300
Detect flag not set	20,000
ACQ flag not set	25,000
ACQ TC flag not set	15,000
DHa > TDH	25,000
LMax/4 < AGC	5,000
Total points typically discarded	35,000

(Note: Total is not cumulative; data points often fail more than one flag.)

This may seem like a very large number of rejections, but the vast majority arises from loss of lock over land and ice. The oceans are usually very well sampled, although certain local regions may suffer significant losses. This is often due to the failure of the altimeter to re-acquire lock immediately after the satellite moves from over land or ice to the ocean. (See next section.)

Spacecraft Attitude Effects

GEOSAT maintains a nadir direction for the altimeter antenna by means of a gravity gradient attitude stabilization system. This method gives outstanding mechanical reliability, but allows excursions off-nadir by as much as 1 degree or more. Because the beam width of the altimeter is only 2 degrees, the nadir footprint is not fully illuminated when attitude is greater than about 1 degree, and the altimeter is sometimes unable to track the return pulse. This problem is particularly severe when GEOSAT passes from land (or ice) to water and has resulted in loss of perhaps 5 to 10 percent of data globally. The groundtrack map in figure 2 shows gaps in the northern hemisphere which are due to this attitude problem. For reasons not totally understood, the location and areal extent of these data gaps change slowly with time, and data loss usually occurs both in the northern and southern hemispheres.

Fortunately, our analyses suggest no degradation in quality of altimeter height data as a function of attitude as long as the tracker was functioning normally (i.e., the data passed the quality tests described in the previous section).

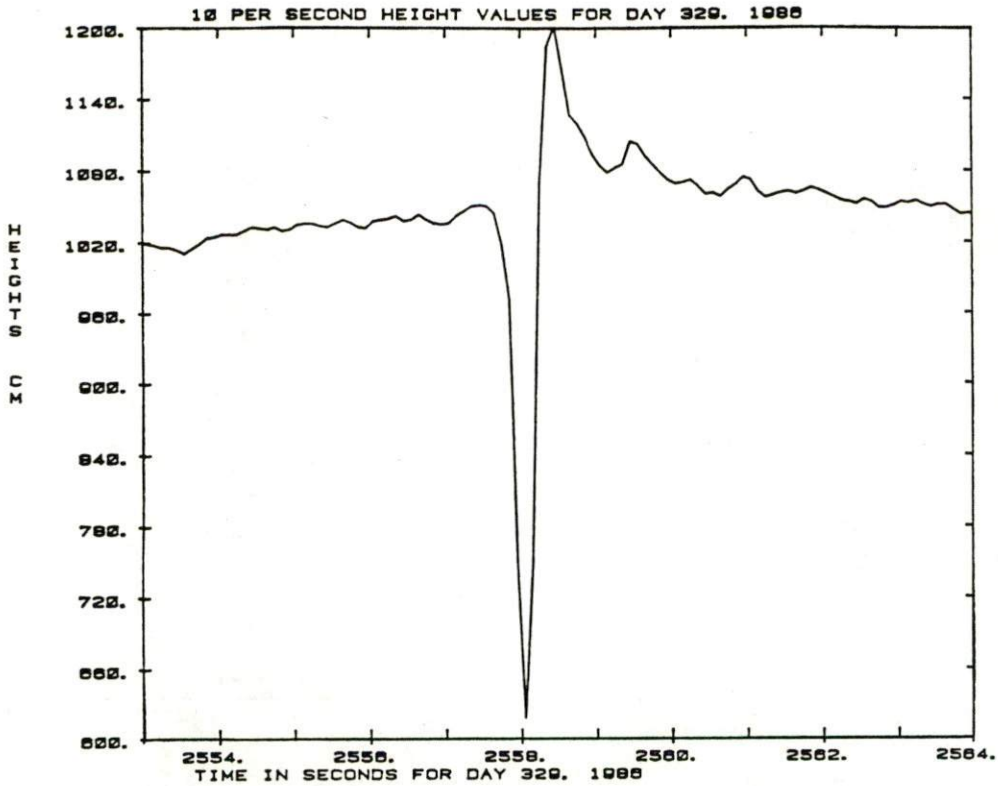

Figure 21.--H values at 10/second rate corresponding to the large anomaly of sigma H in figure 6 near 2600 seconds of time.

Although attitude angles as large as 1.3 degrees may be found, we believe that all ocean heights on the GDR's are unaffected by attitude excursions. The same may not be true for sigma naught and SWH, as these measurements are more sensitive to attitude than the sea height measurement. For these two parameters, it is recommended that the data be used with caution when attitude is greater than approximately 1.1 degrees. However, each user should decide what data to keep based on individual evaluations.

Effect of Rain Cells

Microwave radar altimeter measurements are affected only slightly by tropospheric water vapor, but presence of heavy rain in the footprint causes drastic degradation. Although the altimeter continues to track the return pulse, the height data are not useable and should be edited. The following figures illustrate in detail how the editing can be done.

The sample plot of sigma H in figure 6 shows a severe spike near 2600 seconds. In figure 21 we have plotted the 10/second heights during the period of the spike. Sigma H is shown on the same scale in figure 22. At the 10/second rate the systematic changes in sea height are much too large to be short wavelength geoid undulations. A corresponding plot of AGC in figure 23 shows an abrupt drop of 2 db at the time of the anomaly. Based on previous experience with SEASAT data, the proper interpretation of the H, SWH, and AGC anomalies is that the groundtrack traversed a rain cell. In general, such data should be edited, and the most reliable quantity to use for editing is sigma H.

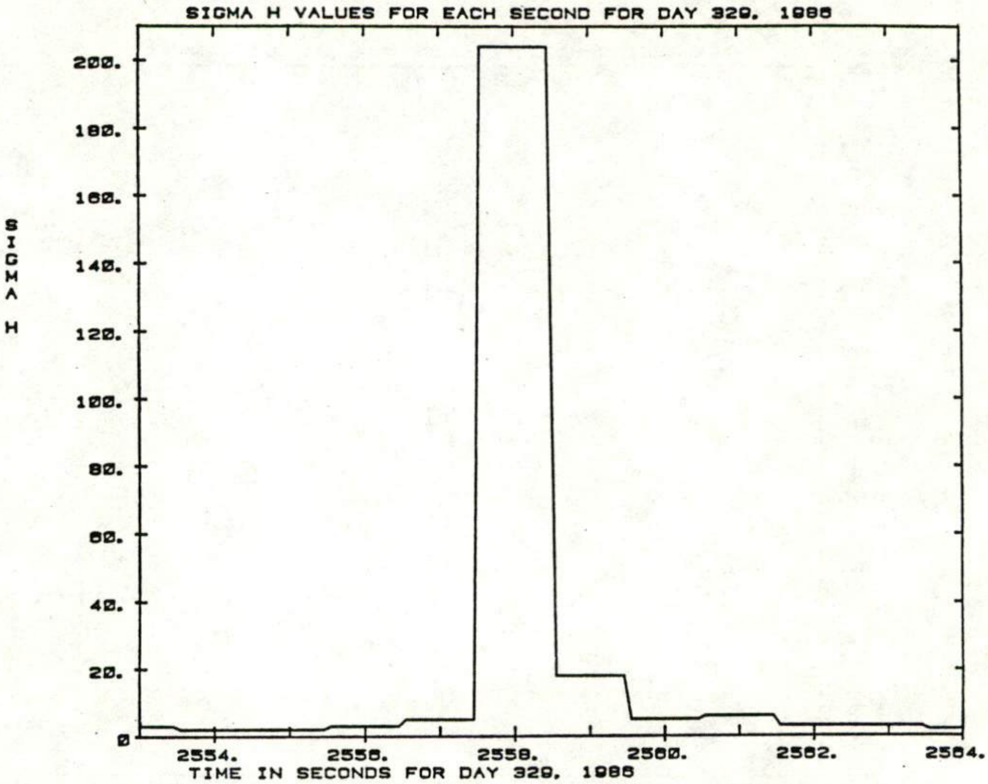

Figure 22.--Sigma H values corresponding to profile in figure 20.

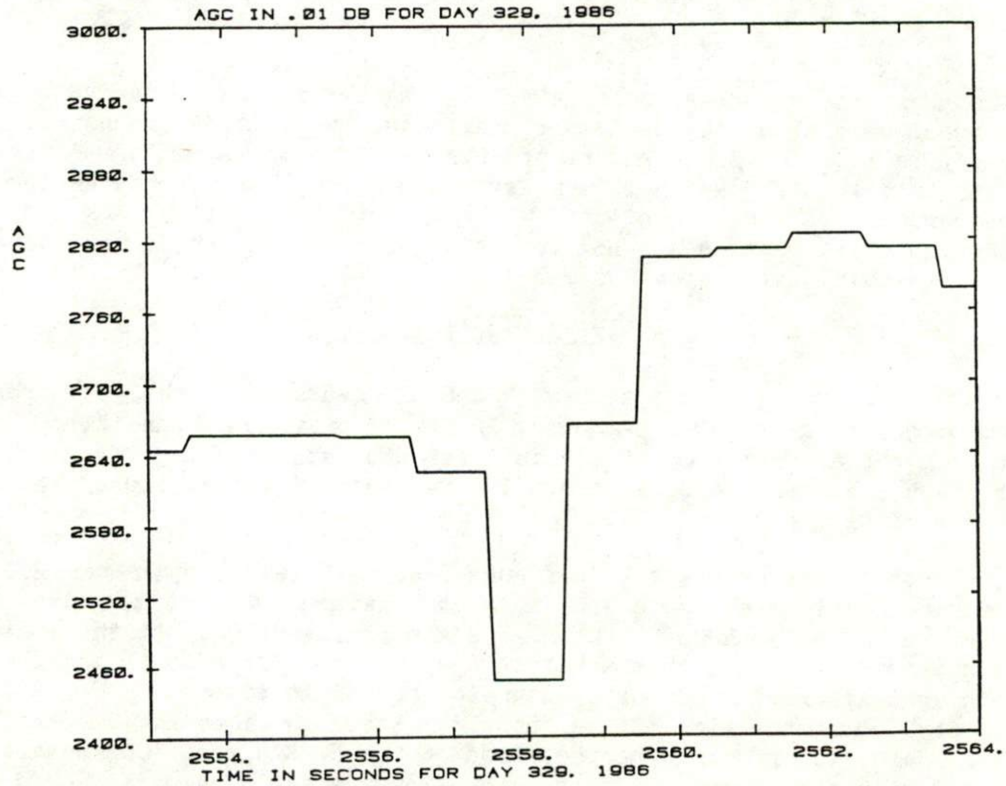

Figure 23.--AGC values corresponding to profile in figure 20.

Solid and Fluid Tide Models

The ERM GDR's contain the solid tide correction computed from the model of Cartwright and Tayler (1971), and an 11-component ocean tide model due to Schwiderski (1980). Error of the solid tide model is unlikely to exceed 1 cm, and error of the fluid tide correction is estimated to be 10 cm (1 sigma) in deep oceans. SEASAT experience showed that much larger errors could occur near land (e.g., the Patagonian Shelf) so investigators should use caution near land areas. In nearly all investigations that use GEOSAT data, tide model uncertainty is not likely to be a factor. Figure 15 shows the solid tide correction for a sample pass. It is obviously of very long wavelength and any error in it will be eliminated in a crossover or collinear adjustment used to remove ephemeris error. Figure 16, which illustrates the total ocean tide signal along the groundtrack, has a richer spectrum than the solid tide, but again an investigation must cope only with the error in the correction. If this error is a fraction of the total effect, it is seen from figure 16 that tide model error will usually be eliminated along with ephemeris error.

Ionosphere Correction

GEOSAT has a single-frequency altimeter resulting in an effect on the microwave path length that could be as much as several decimeters. However, GEOSAT has been flown during a period of low solar activity, so the effect has rarely exceeded 5 cm. Figure 20 shows the ionosphere correction for the daylight portion of the pass considered previously. The correction is shown to be of long wavelength, a result of the model being used to calculate the correction only considering long wavelength effects. However, these are the dominant ones, so that like solid and fluid tide model errors, errors of the ionosphere correction will be reduced to insignificance when a crossover or collinear adjustment that eliminates ephemeris error is performed.

In order to evaluate the accuracy of the GEOSAT ionosphere model, we used it to calculate values for the SEASAT time period. Figure 24 displays the correction from the GEOSAT model, and the correction computed at the Jet Propulsion Laboratory from Faraday rotation measurements. The close agreement of the corrections suggests that the GEOSAT model will suffice for most investigations.

Wet and Dry Troposphere Corrections

The weakest of all of the corrections provided on the GEOSAT GDR's is for the wet troposphere effect. This effect can reach approximately 35 cm in magnitude, and is spatially highly variable in many areas. Figures 17 and 18 show the correction as determined from FNOC data, and a climatological estimate based on NIMBUS-7 satellite data. Agreement is qualitatively excellent, but 10-centimeter differences between the estimates are not uncommon. The situation for this important correction may improve in the near future with the upcoming launch of the SSMI (Special Sensor Microwave Imager) on a Defense Meteorological Satellite that will measure water vapor during the GEOSAT ERM. In addition, it should be possible to use NIMBUS-7 SMMR data to retrieve water vapor for the period 1985-87.

The dry troposphere correction is better known than the wet troposphere. Figure 19, which displays the correction computed from FNOC barometric pressure data, shows that the correction is always about 2.2 m with an additional relatively small (~10 cm) long wavelength variation. As in the case of many of the other corrections, errors in the dry troposphere correction will be largely eliminated along with ephemeris error in crossover or collinear adjustments of data.

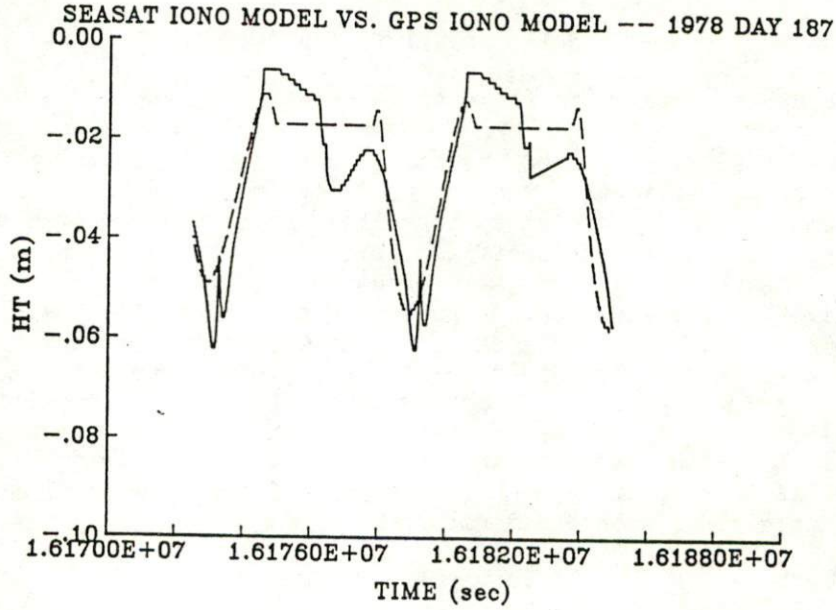

Figure 24.--Comparison of JHU/APL model ionosphere correction (dashed line) for two revolutions of SEASAT in 1978 with NASA/JPL model values (solid line).

Geoid Heights

Geoid heights computed from the 1-degree resolution model of Rapp (1978) are included on the GDR records. These geoid heights were derived from a combination of satellite and surface gravity data and do not include the permanent dynamic sea surface topography; i.e., no altimeter data were used in the determination of this geoid. Subtracting these geoid heights from the GDR sea surface heights reduces the variability of the altimeter heights from about 100 m to a few meters. This remaining difference should not in general be interpreted as ocean dynamic heights because of geoid model uncertainties and especially GEOSAT height ephemeris error.

Data Time Tag Accuracy

SEASAT data required a time tag correction of 79 msec. Although we can say that no such large error exists in GEOSAT data, initial attempts at the time of writing this document have not been able to establish an unambiguous value. However, in the absence of evidence of a problem, a value of zero should be used.

Electromagnetic Bias Correction

SEASAT sea surface heights needed to be increased by about 6.5 to 7 percent of significant wave height (SWH) and GEOS-3 heights required a correction of 2 percent of SWH (Douglas and Agreen 1983). The disparity of 5 percent between SEASAT and GEOS-3 was due to a hardware bias on SEASAT and was in addition to the real effect of microwave ranging that would occur for any altimeter. Preliminary estimates from ERM data give 2.0 percent ± 0.6 percent, consistent with GEOS-3 results. At the present time we thus recommend using 2 percent for the correction.

$$H\ (\text{corrected}) = H + (SWH * .02)$$

Crossover Evaluation and Adjustment

A critical issue for ERM data users is the accuracy of the ephemeris computed by NAG to position GEOSAT above the reference ellipsoid. The rms crossover value for any given 17-day cycle of the ERM is approximately 4 m. Ephemeris error of course propagates directly into sea surface heights. In order to evaluate the importance of this error on oceanographic investigations, we have attempted to model orbit error by a simple quadratic polynomial for each pass whose coefficients were determined in a least squares crossover adjustment. The test area was the Pacific Ocean between 40 degrees north and south latitude. Simultaneous removal of a quadratic function from each pass resulted in a postadjustment rms of only 7.5 cm. Clearly the error in the NAG ephemeris is at long wavelengths and will have no effect on investigations of oceanic height variability at wavelengths out to at least several thousand kilometers.

ACKNOWLEDGMENTS

We are grateful to the U. S. Navy for granting us access to the GEOSAT data and to Johns Hopkins University Applied Physics Laboratory for cooperating with us in our research. In particular, we thank R.Adm John Seesholtz, Oceanographer of the Navy, Cdr. Frank Wooldridge, U. S. Navy GEOSAT Project Manager, Dr. Vincent Pisacane, Director of JHU/APL Space Department, Dr. Charles Kilgus, JHU/APL GEOSAT Project Manager, and Dr. Julius Goldhirsch, JHU/APL. Credit is also due R.Adm. John Bossler and R.Adm. Wesley Hull of NOAA, Paul Wolff, Assistant Administrator for NOAA's National Ocean Service, and William Kaula, Chief of NOAA's National Geodetic Survey, for their enthusiastic support.

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APPENDIX A.--GEOSAT DATA ORDER FORM

GEOSAT Data Order Form

BACKGROUND:
The National Oceanographic Data Center (NODC) has been designated as the archival and dissemination facility for Geophysical Data Records from the Exact Repeat Mission (ERM) of the U.S. Navy Geodetic Satellite (GEOSAT). During the ERM, which began on November 8, 1986, GEOSAT is collecting data along an orbital ground track with a 17-day repeat cycle. GEOSAT Sensor Data Records (SDRs) are converted to Geophysical Data Records (GDRs) by a group within the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA). This group transmits the GEOSAT GDRs to the NODC on 6250 bpi magnetic tapes. Each tape contains 34 days of GEOSAT data, or two 17-day repeat cycles. The GEOSAT GDRs provide global ocean significant wave heights and other ocean data derived from GEOSAT altimetry measurements.

The NODC receives GEOSAT data approximately 30 to 60 days after observation. A new data tape is received at the NODC about every five weeks. Copies of the GEOSAT GDR data tapes are provided to customers on either an annual subscription or individual order basis. Non-U.S. citizens must request these data through the science officer of their country's embassy in the United States. To request GEOSAT data from the NODC, please read carefully and fill in the following portion of this order form as appropriate. Inquiries about obtaining GEOSAT data and completed order forms should be directed to:

National Oceanographic Data Center
User Services Branch
NOAA/NESDIS E/OC21
Washington, DC 20235

Telephone: 202-673-5549 or FTS 673-5549

Electronic Mail: OMNET/MAIL mailbox "NODC.WDCA"

ANNUAL SUBSCRIPTION:

☐ I would like to receive GEOSAT GDR data on annual subscription: Twelve 34-day data tapes (6250 bpi).

Cost: $1200 *($100 per tape, $15 less than tapes ordered individually.)*

INDIVIDUAL ORDER:

☐ I would like to receive GEOSAT GDR data covering the time period from

Day ________________ Month ________________ Year ________________ to

Day ________________ Month ________________ Year ________________

Please let me know the number of tapes that span this period.

Cost: $115 per tape (6250 bpi)
$100 per tape (1600 bpi) *(One 6250 tape equals approximately four 1600 bpi tapes.)*

FORMAT OPTIONS:

All GEOSAT GDR tapes are in <u>binary</u> format; available options are:

☐ 6250 bpi, non-labeled, multifile (one file per day), Hewlett-Packard data structure

☐ 6250 bpi, standard label, multifile (one file per day), ANSI standard (VAX) data structure

☐ 1600 bpi, standard label, multifile (one file per day), ANSI standard (VAX) data structure
(Available on individual orders only, not on subscription.)

METHOD OF PAYMENT:

☐ Check or money order (Make payable to "Dept. of Commerce/NOAA/NODC".)

☐ Purchase order (#______________________________)
(Non-Federal customers may use purchase orders only with prior authorization from NODC.)

☐ Visa ☐ MasterCard

Account No. ______________________________ Expiration Date ______________

Name ____
(Exactly as it appears on card)

Signature ____

Telephone No. (with area code) ______________________________________

DOCUMENTATION:

Subscribers and customers submitting individual data orders will receive a copy of the *GEOSAT Altimeter Geophysical Data Record (GDR) User Handbook* produced by NOS; in addition each tape will be accompanied by a brief data inventory giving the date and beginning and ending time and geographic position (latitude and longitude) of each data file (day) on the tape, and a plot of the GEOSAT ERM ground track for the data.

AGREEMENT:

I understand that the NODC should be notified of any redistribution of these data. I further understand that GEOSAT data subscriptions may be cancelled and refunds made for the balance of subscription payments. Subscription cancellations, however, require two weeks written advance notice to the NODC.

Signature ______________________________________ Date ______________

Name ____

Title/Department ____

Organization ____

Street Address ____

City ______________________________ State __________ Zip ________

Country ____

Telephone No. (with area code) ______________________________________

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service
National Oceanographic Data Center
Washington, DC 20235

March 1987