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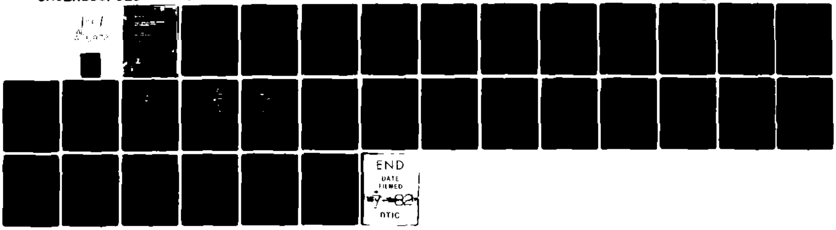

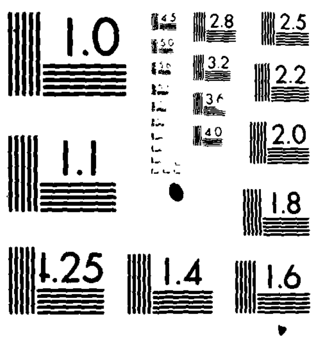

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Measurements from the SEASAT satellite radar altimeter are combined with the Doppler precise orbit, corrected for atmospheric and environmental effects, and reduced to along-track geoid heights and vertical deflections by an adaptive Kalman smoother, which is based upon a third-order Markov process. The altimeter data processing system at the Naval Surface Weapons Center (NSWC) is described in this report.

FOREWORD

The radar altimeter aboard the SEASAT satellite provided data from which best-estimated along-track geoid heights and vertical deflections over the oceans are derived. During the SEASAT satellite mission, 26 June 1978 to 9 October 1978, approximately 1000 revolutions of altimeter data were collected. This report describes the NSWC/DL SEASAT altimeter data-processing system for obtaining the best-estimated along-track geoid heights and vertical deflections. The project was conducted in the Space and Surface Systems Division under the sponsorship of Defense Mapping Agency.

This report was reviewed by Ralph L. Kulp, Jr., Head, Space and Ocean Geodesy Branch, and Carlton W. Duke, Jr., Head, Space and Surface Systems Division.

Released by:

C. A. Fisher

C. A. FISHER, Head
Strategic Systems Department

A

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ABBREVIATIONS AND DEFINITIONS

1. FNWC - Fleet Numerical Weather Central, Monterey, California (now Fleet Numerical Oceanography Center)
2. IGDR - Interim Geophysical Data Records
3. SDR - Sensor Data Record
4. FGD - Filtered Geophysical Data
5. UGD - Unfiltered Geophysical Data
6. SGD - Segmented Geophysical Data
7. NASA - National Aeronautics and Space Administration
8. PMDF - Project Master Data File
9. rev - One revolution of the satellite around the earth commencing at the equator (ascending node) and ending at the equator
10. JPL - Jet Propulsion Laboratory, Pasadena, California

INTRODUCTION

SEASAT, a follow-on of GEOS-3, was a National Aeronautics and Space Administration (NASA) satellite for measuring global ocean dynamics from space. The spacecraft was launched 26 June 1978 with instruments aboard that provided data on wave height, wind speed and direction, ice fields, ocean surface topography and weather. Data over the oceans was stored aboard and transmitted when in the range of the observation stations located at Merritt Island, Florida, Madrid, Spain, and Fairbanks, Alaska. Goddard Space Flight Center in Greenbelt, Maryland obtained the data collected by the 3 stations and distributed it to the Jet Propulsion Laboratory (JPL) in Pasadena, California, and Fleet Numerical Weather Center (FNWC) in Monterey, California, where data was converted to engineering units and some preprocessing done. Early in the mission, data from Fairbanks was transmitted by telecommunications satellite to FNWC, but this process was discontinued because of an operational problem. The mission ended 9 October 1978 with approximately 1000 revolutions (revs) of data collected. As mentioned earlier, the spacecraft carried a number of different instruments; however, this report is only concerned with the radar altimeter.

The purpose of the radar altimeter was to measure significant wave height at the subsatellite point and the precise altitude between the satellite and the ocean surface. The altitude when combined with the Doppler precise orbit [Colquitt et al., 1980], atmospheric and environmental effects, gives the sea-surface topography, which is an approximation of the geoid height. This report describes the SEASAT altimeter data-processing system which employs the altitude measurements in the determination of best-estimated along-track geoid heights and vertical deflections.

SEASAT ALTIMETER DATA-PROCESSING SYSTEM

GENERAL DESCRIPTION

The Naval Surface Weapons Center (NSWC) altimeter data-processing system entails the following: the generation of the Interim Geophysical Data Record (IGDR) tapes; separation of revs and time-continuous segments of revs; computation of sea-surface heights; and application of an adaptive Kalman smoother to obtain best-estimated along-track geoid heights and vertical deflections. An overview of the processing system is shown in Figure 1. At FNWC, Project Master Data File (PMDF) tapes are used in the generation of Sensor Data Record (SDR) tapes, which are then used as input to NSWC software (REDUCE). REDUCE outputs IGDR tapes which were shipped from FNWC to Dahlgren. Formats for the IGDR and SDR tapes and the REDUCE program are described in an intralaboratory Technical Note (80-96) by J. M. Futcher, Jr. In brief, the REDUCE program separates land and ocean data, computes atmospheric and environmental corrections, and prefilters and aggregates the data. The altimeter data given on the SDR at 10 points per second (pps) can be aggregated by REDUCE to a rate specified by an input parameter. Data was aggregated to 2 pps for the overall SEASAT altimeter data reduction.

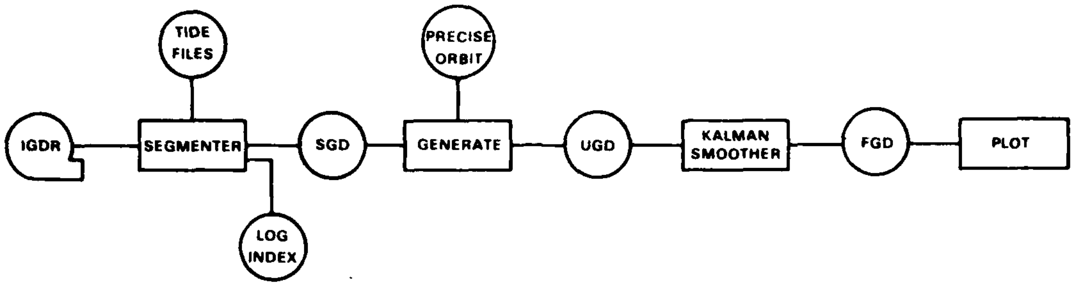


Figure 1. SEASAT Radar Altimeter Data-Processing System

The IGDR tapes are the major input to the altimeter data-processing at NSWC. The tapes contain such information as rev number, time, latitude, longitude, altimeter range, and atmospheric and environmental corrections. Each tape contains 1 to 8 data files where each file corresponds to a dump of the recorder on board the satellite. A file is made up of records, one for each data point. Data within a satellite rev, revs within a file, and most files are time ordered.

Data files created during the processing are the Log Index, Segmented Geophysical Data (SGD), Unfiltered Geophysical Data (UGD), and Filtered Geophysical Data (FGD). The SGD and UGD files are temporary but can be saved for special purposes through program control.

The FGD file is the major output from the altimeter data-processing system and contains basically sea-surface heights, corrections, best-estimated along-track geoid heights and vertical deflections. Both the IGDR and FGD are maintained at NSWC and have been distributed to other specified agencies for analyses and for determining other geodetic parameters. The next 4 sections will contain brief descriptions of the major programs used in the processing.

SEGEMENTATION OF DATA INTO REVS

The function of the Segmenter program entails separation of data from the IGDR tapes into revs, division of revs into time-continuous segments, calculation of tide corrections, determination of some environmental corrections, and creation of the Log Index and the Segmented Geophysical Data files. Data for each rev is divided into time-continuous segments and processed as a separate entity. Time-continuous segments are determined by examining the rev data for the existence of a constant time interval ($\Delta t \approx .5$ sec). If the time interval is not approximately .5 sec, but <5 sec, a linear interpolation procedure is used to dub in the number of points required to bridge the interval. If the interval is >5 sec, the previous time-continuous segment ends and a new segment begins.

For each altimeter measurement the ocean tide correction is determined by the Schwiderski Ocean Tide model (1979). This model consists of the 7 leading tide components: M_2, S_2, N_2, K_2, K_1, O_1, and P_1 of the solid earth, oceans, and the tidal yielding of the solid earth. Such information as the time of initial point in segment, time interval between points, longitude of the ascending node, equator crossing time, and number of points in a segment is required by the model.

The timing correction (Appendix B) is applied to the observation time in the Segmenter and corrections for the tilt/sea state, geometric factor, electrical delay distance are computed. Algorithms for these corrections are given in Appendix B.

In the altimeter data, erroneous values of latitude and longitude were found periodically. When these values were encountered corresponding corrections dependent upon latitude and longitude were set to zero or a standard value.

The Log Index file created by the segmenter is used as input to an index program, which provides descriptive information for each rev and segment of rev in the complete SEASAT data base. The SGD file is used as input to the second major program, GENERATE, which determines the sea-surface heights.

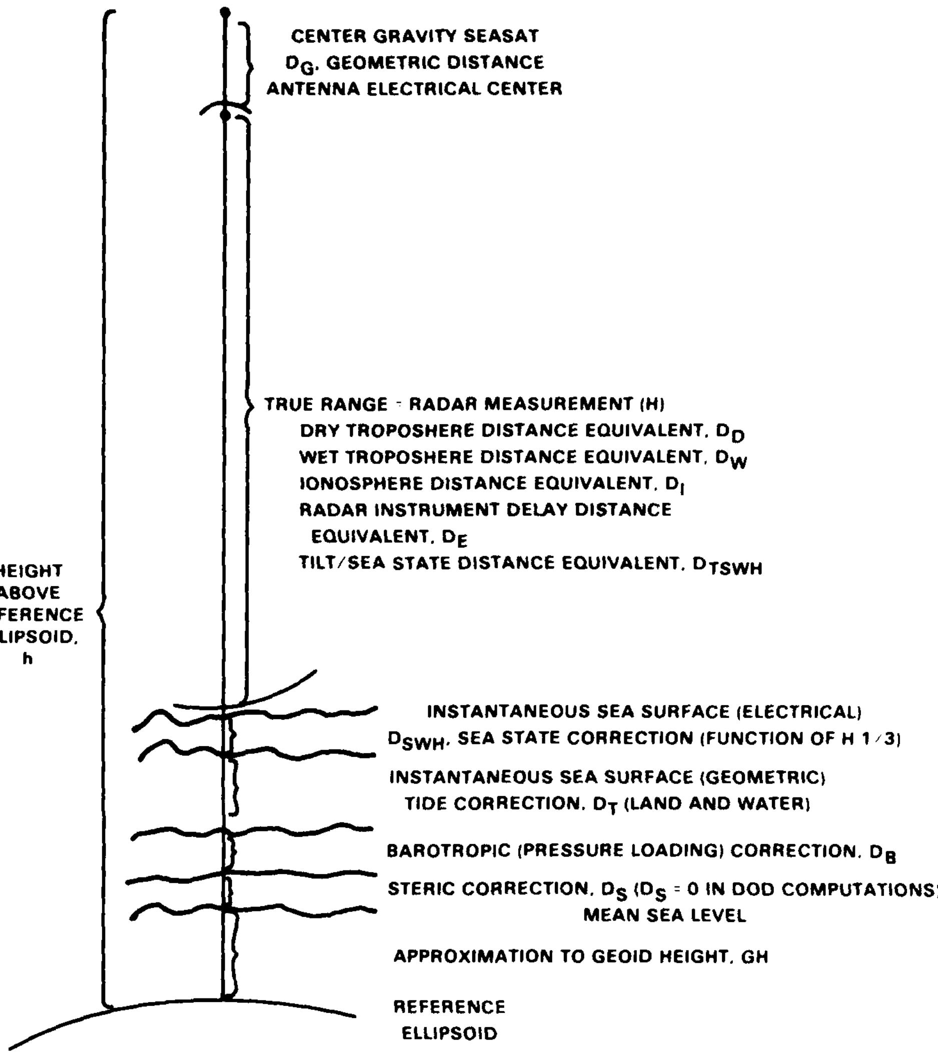
COMPUTATION OF SEA-SURFACE HEIGHTS

The height of the altimetric geoid relative to the reference ellipsoid (sea-surface height) is obtained by combining the altimeter range with the Doppler precise orbit and applying environmental and atmospheric effects. The time of the altimeter range is used in an 8-point Lagrangian interpolation to compute subsatellite position, latitude and longitude. Algorithms for determining the subsatellite position and sea-surface height were provided by Ray Manrique and are given in Appendix A. Corrections applied to the altimeter range are shown in Figure 2.

The computer program, GENERATE, performs the computation of the sea-surface height and outputs the temporary UGD file for use in the filtering section of the data-processing system.

GENERATION OF BEST-ESTIMATED ALONG-TRACK GEOID HEIGHTS AND VERTICAL DEFLECTIONS

The sea-surface heights are reduced to best-estimated along-track geoid heights and vertical deflections by a Kalman smoother based upon the third-order Markov process (Jordan, 1972). The Kalman smoother for SEASAT was provided by Dr. C. J. Cohen and is described in West et al. (1977). An adaptive



$$\boxed{\begin{gathered} GH = h - H - D_G + D_E + D_D + D_W + D_I \\ - D_T - D_B + D_{TSWH} - D_S \end{gathered}}$$

NOTE

1. HIGH TIDE (D_T) ARE ASSUMED POSITIVE (+)
2. BAROTROPIC (D_B) ARE POSITIVE (+), IF $P < 1013$ mb
3. CURRENT CORRECTION OMITTED
4. SEA STATE CORRECTION, D_{SWH} IS COMBINED WITH D_{TSWH}

Figure 2. Atmospheric and Environmental Corrections

algorithm written by Ugincius (1977) is used for improvement of a priori parameters; auto-correlation distance, geoid-height variance, and the noise standard deviation required by the smoother. The autocorrelation distance is determined for 1000 km spans of data and spans with similar autocorrelation values are grouped as a segment.

Magnitudes of the geoid heights and vertical deflections sometimes fall outside the expected range. These values may be caused by such factors as loss of bits, and the presence of land data near the coastlines and over small land masses. Geoid-height values less than -125 m and greater than +125 m are set to -125 m or +125 m, respectively. Vertical deflections are handled similarly, those values less than -100 arc sec and greater than +100 arc set are set to -100 arc sec or +100 arc sec, respectively. If either of the two conditions exist the longitude value is made negative to indicate that data has been dubbed in. A flag word in the FGD file is also set to reflect this data. In the smoothing procedure, dubbed-in data points have zero weights.

Output from the Kalman smoother program is the FGD file, which consists of filtered data from one satellite rev. Such information as sea-surface heights, corrections applied, statistical information, and best-estimated along-track geoid heights and vertical deflections make up the FGD file. The rev data base consists of over 900 FGD files on 20 device sets. Each FGD file is a permanent file with file names of the form FGDRRRRR where RRRRR is the rev number. The rev data base was used in the generation of an area data base that consists of 48 permanent files on 9 device sets. The area base differs from the rev base in that erroneous data points at both ends of a segment are eliminated and the data has been aggregated to 1 pps and data in an area only contains the portion of the rev that passes through the area. The surface of the earth is divided into areas as shown in Figure 3. Area file names are of the form FGDSSAREAXX where SS means SEASAT and XX is the area number.

PLOT OF FILTERED GEOPHYSICAL DATA FILE

Parameters from the FGD file may be plotted on the SD4060 or Tektronix (4051) plotting equipment. Parameters which can be plotted versus time are the following: sea-surface heights, geoid heights (Figure 4), vertical deflections (Figure 5), significant wave heights (Figure 6), and the automatic gain control (Figure 7). A complete satellite rev may be shown on one plot frame or divided into time spans and each time span shown on one frame.

CONTROL PROGRAM

Reduction of the altimeter data is controlled by the SEASAT Radar Altimeter Data-Processing System (SRAPS) computer program (J. D. Clark, unpublished user's guide). SRAPS gives the user the flexibility in a single computer job to control the execution of the set of computer programs required to reduce the SEASAT altimeter measurements, taken over the oceans, to filtered along-track geoid heights and vertical deflections. The computer programs are executed in the order described in Figure 1. A file containing the information for reducing the altimeter data is given to the SRAPS program, which generates job control necessary for processing a set of data. The job control is then routed to the system input queue.

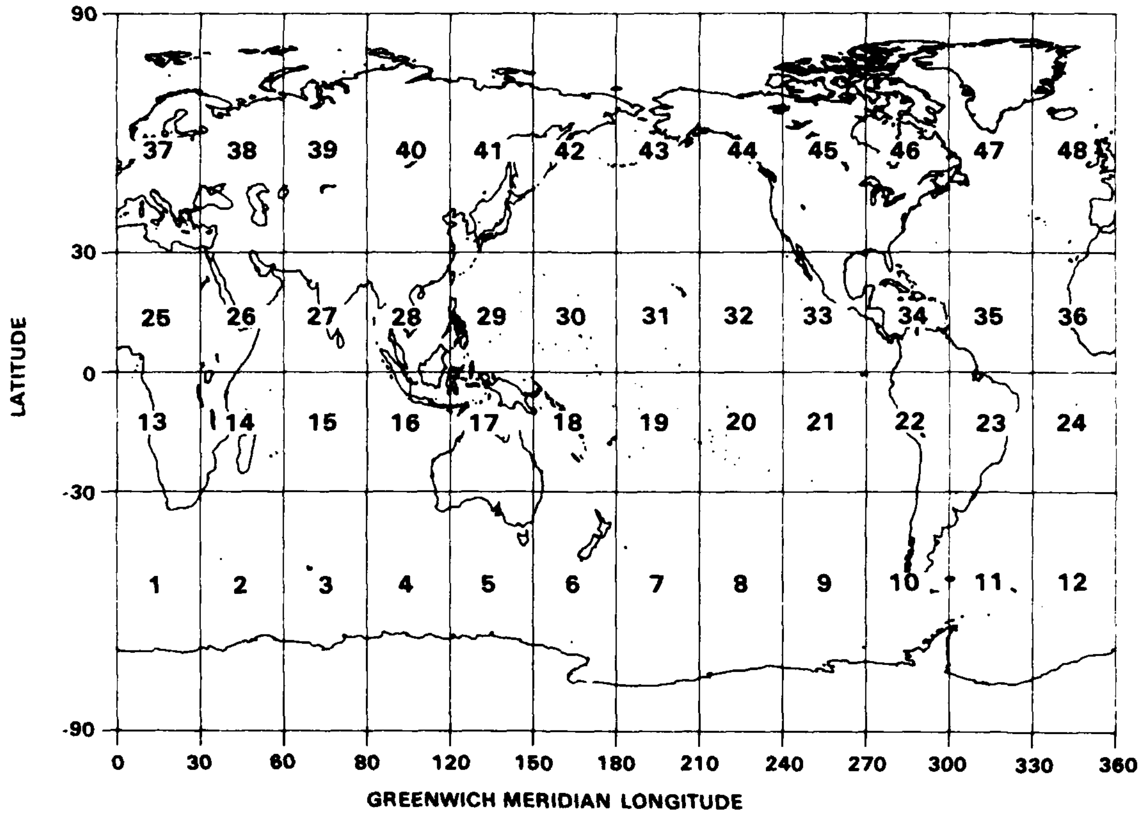


Figure 3. Filtered-Area Data Base

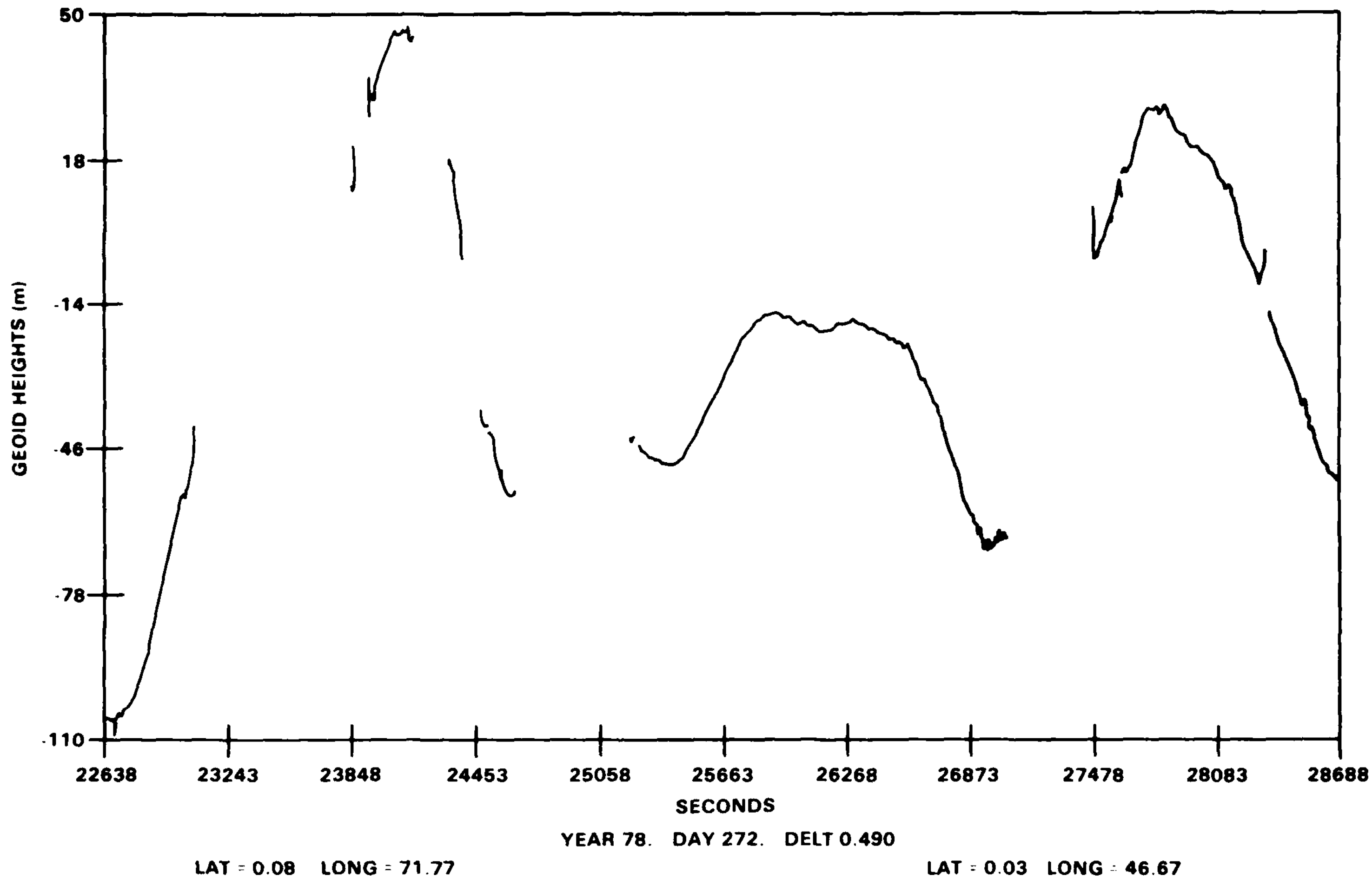


Figure 4. Along-Track Geoid Heights for Rev 1348

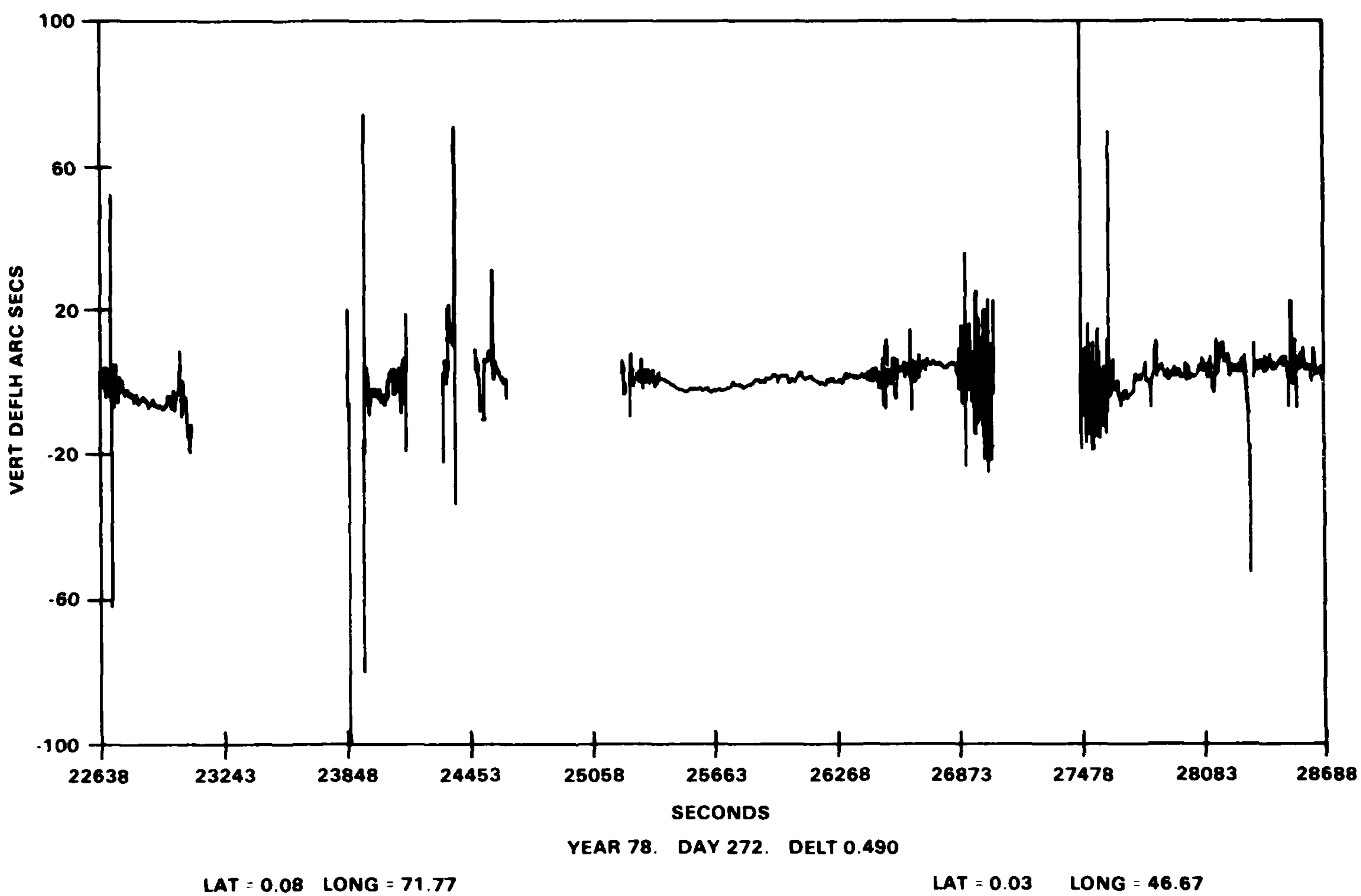


Figure 5. Along-Track Vertical Deflections for Rev 1348

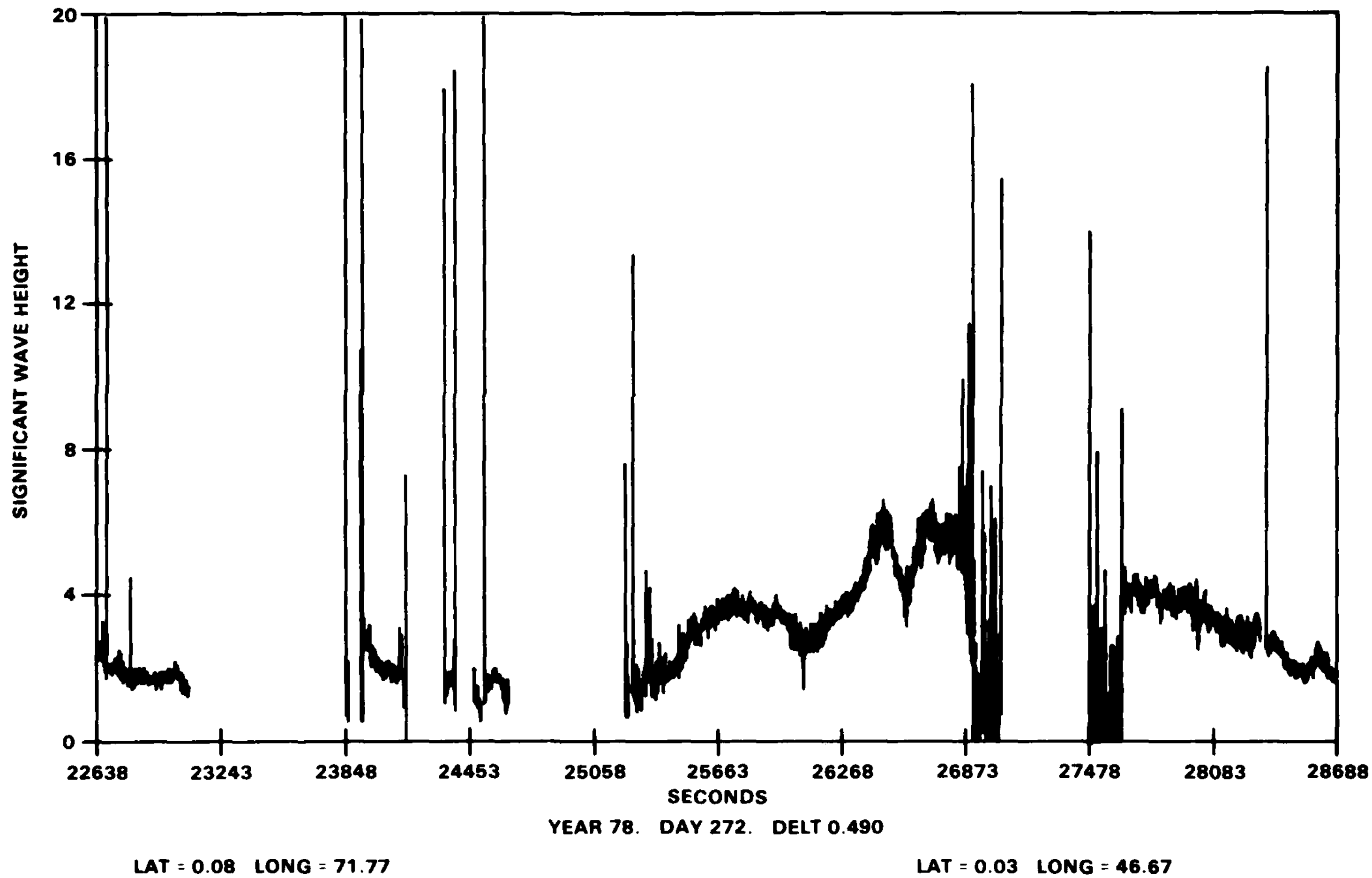


Figure 6. Significant Wave Heights for Rev 1348

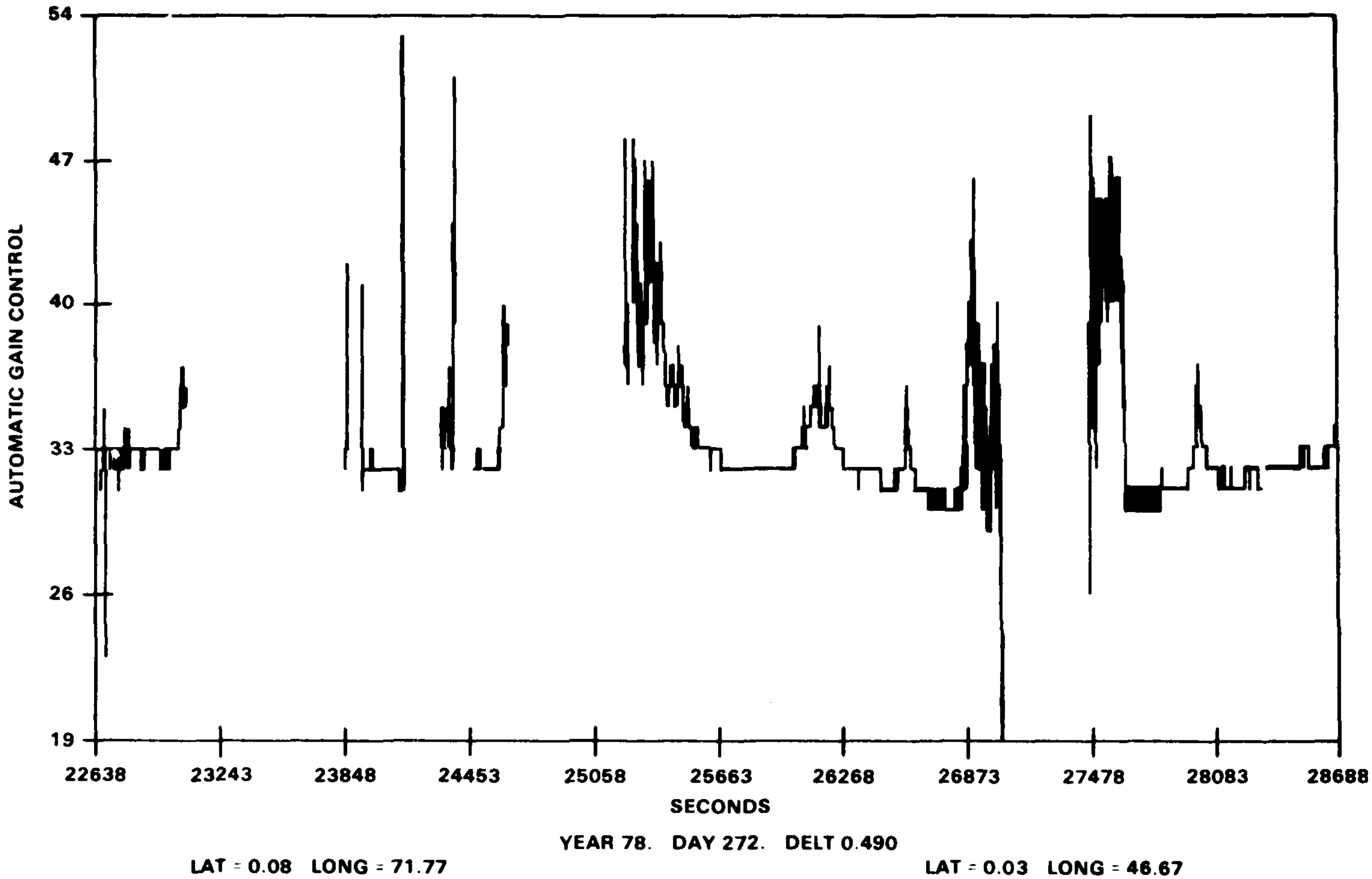


Figure 7. Automatic Gain Control for Rev 1348

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APPENDIX A

SEA-SURFACE HEIGHT AND SUBSATELLITE POSITION

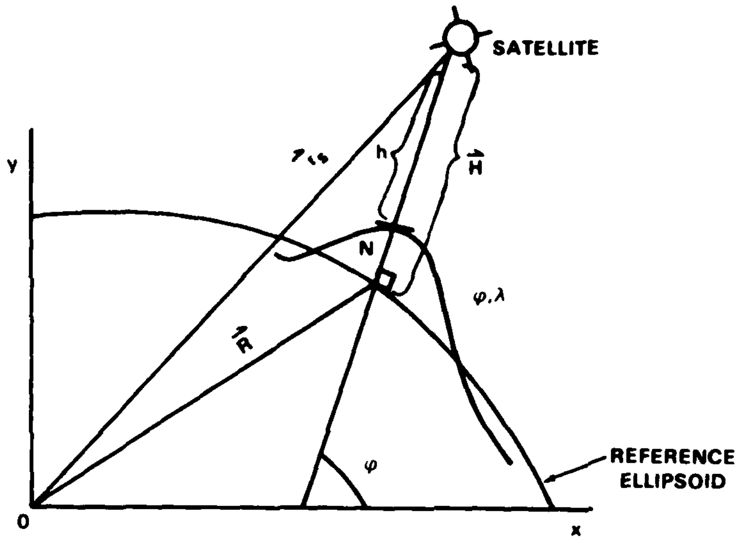

Figure A-1. Height of Geoid Above Reference Ellipsoid

h - altimetric height above the geoid (km)

r_s - distance of satellite from center of reference ellipsoid (km)

N - height of geoid above reference ellipsoid (m)

ϕ - geodetic latitude (deg)

H - geometric height above the ellipsoid (km)

a - semi-major axis of reference ellipsoid (km)

e - eccentricity of the reference ellipsoid

$N = H - h$

where

$$H = \frac{z_s}{\sin\phi} - \frac{a(1-e^2)}{\sqrt{1 - e^2 \sin^2\phi}}, \text{ and}$$

h is corrected for atmospheric and environmental effects as shown earlier in Figure 2.

$$\tan\phi_o = \frac{z_s}{\sqrt{x_s^2 + y_s^2}},$$ starting value for ϕ, and

$$\tan\phi_{k+1} = \frac{1}{\sqrt{x_s^2 + y_s^2}} \left[z_s + \frac{ae^2 \tan \phi_k}{\sqrt{1+(1-e^2)\tan^2\phi_k}} \right]$$

Iterate until $\left|\tan \phi_{k+1} - \tan \phi_k\right| \leq \tau$,

where $\tau = (1 + \tan^2\phi_k) \times 10^{-9}$, then

$$\phi_{k+1} = \tan^{-1}\left\{ \frac{1}{\sqrt{x_s^2 + y_s^2}} \left[z_s + \frac{ae^2 \tan \phi_k}{\sqrt{1+(1-e^2)\tan^2\phi_k}} \right] \right\}.$$

$$\lambda_i = \tan^{-1} \frac{y_s}{x_s}, \text{ where } 0 \leq \lambda_i \leq 2\pi$$

$\phi_i = \phi_{k+1}$ and λ_i are computed for each observation time, t_i.

$a = 6378.145$ km, $e^2 = 2f - f^2$, and $f = 1/298.25$

APPENDIX B

ATMOSPHERIC AND ENVIRONMENTAL CORRECTIONS

1. Tilt/Sea-state Correction to Height

The Wallops Flight Center Tilt/Sea state Correction Tables (B. F. Townsend, 3/26/79) were fitted with the following bi-linear (Anderle function):

$$\Delta H(cm) = -5. + 9.33(T) + 1.0625(SWH) + 1.75(T)(SWH),$$

where: T = tilt in degrees,

SWH = significant wave height in meters.

The maximum deviation from the tabular values is ~ 10 cm.

The correction is labeled in the printed output as Tilt/SWH Correction to H.

2. The SWH correction obtained from a similar fit is given below.

$$\Delta H^{1/3}(m) = \Delta SWH = -.32 \times SWH \times T^2$$

where, T = tilt in degrees and $\Delta H^{1/3}$ is given in meters.

3. Wet Tropospheric Correction

The wet trospheric correction, D_W, is computed from input surface temperature and partial pressure of water vapor given below.

$$D_W(cm) = 86400.\ P_W/(273. + T_S)^2,$$

where

P_W = partial pressure of water vapor (mB),

T_S = surface temperature, deg. C.

If P_W is unavailable, use 12.272.

If T_S is unavailable, use 0.

4. Dry Tropospheric Correction

The dry tropospheric correction D_D, is computed from input pressure and latitude as given below.

$$D_D(cm) = \frac{(2.277 - .011 \cos \phi)}{10} P,$$

where

ϕ = latitude from location data,

P = pressure (mB).

If P is unavailable, use 1013.3.

5. Barotropic Correction

The barotropic correction, D_B, computed from input atmospheric pressure as given below.

$$D_B(m) = -.009948(P_a - 1013.0),$$

where

P_a = atmosphereic pressure (mB) supplied by FNWC.

6. Ionospheric Refraction Correction

The ionospheric refraction model shown in Figure B-1 (Bent, et al., 1975) was developed by James Clynch and Arnold Tucker of Applied Research Laboratory, University of Texas, Austin, Texas and modified by Dr. Ralph Gibson of NSWC. The model uses telecommunications predictions obtained from the Environmental Data Service (now known as National Oceanic and Atmospheric Administration). The ionospheric correction, ΔR, is given by the equation (1) below.

$$\Delta R = \frac{C}{f^2} \int_{r_e}^{r_s} \frac{N(x,y,z)rdr}{\sqrt{r^2 - k^2}}, \quad (1)$$

where $k = r_e \sin z$

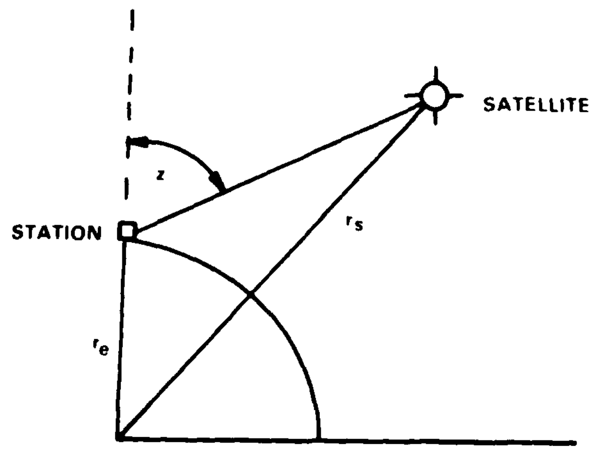

Figure B-1. Ionospheric Refraction Model

For SEASAT altimeter k=0, since the range is straight up and down; therefore the ionospheric refraction correction, D_I, is given by the equation (2) and ranges between 3 and 15 cm with a ± 15% accuracy.

$$D_I(\mathrm{cm}) = \frac{C}{f^2} \int_{r_e}^{r_s} N(x,y,z)\, dr,$$

where

r_s = distance from center of earth to the satellite (km)

r_e = the radius of the earth (km)

f = transmitted frequency (MHz)

C = a known constant (= 8.061389×10^{-5})

$N(x,y,z)$ = electron density (el/cm^3)

The vertical electron-density profile is shown in Figure B-3. The E and F1 layers are modeled by a parabola; F2 layer up to H_mF2 is modeled by a fourth degree curve; H_mF2 to H_{Crit} is modeled by a parabola; and the remaining 3 portions of F2 are modeled by a decaying exponential with decay constants K_1, K_2, and K_3.

PARAMETERS FOR IONOSPHERIC ELECTRON-DENSITY PROFILE

F_oE - Critical frequency of E region

H_mE - Height of maximum ionization of E region

Y_mE - Semithickness of E region

F_oF1 - Critical frequency of F1 region

H_mF1 - Height of maximum ionization of F1 region

Y_mF1 - Semithickness of F1 region

F_oF2 - Critical frequency of F2 region

H_mF2 - Height of maximum ionization of F2 region

Y_mF2 - Semithickness of lower and middle F2 region

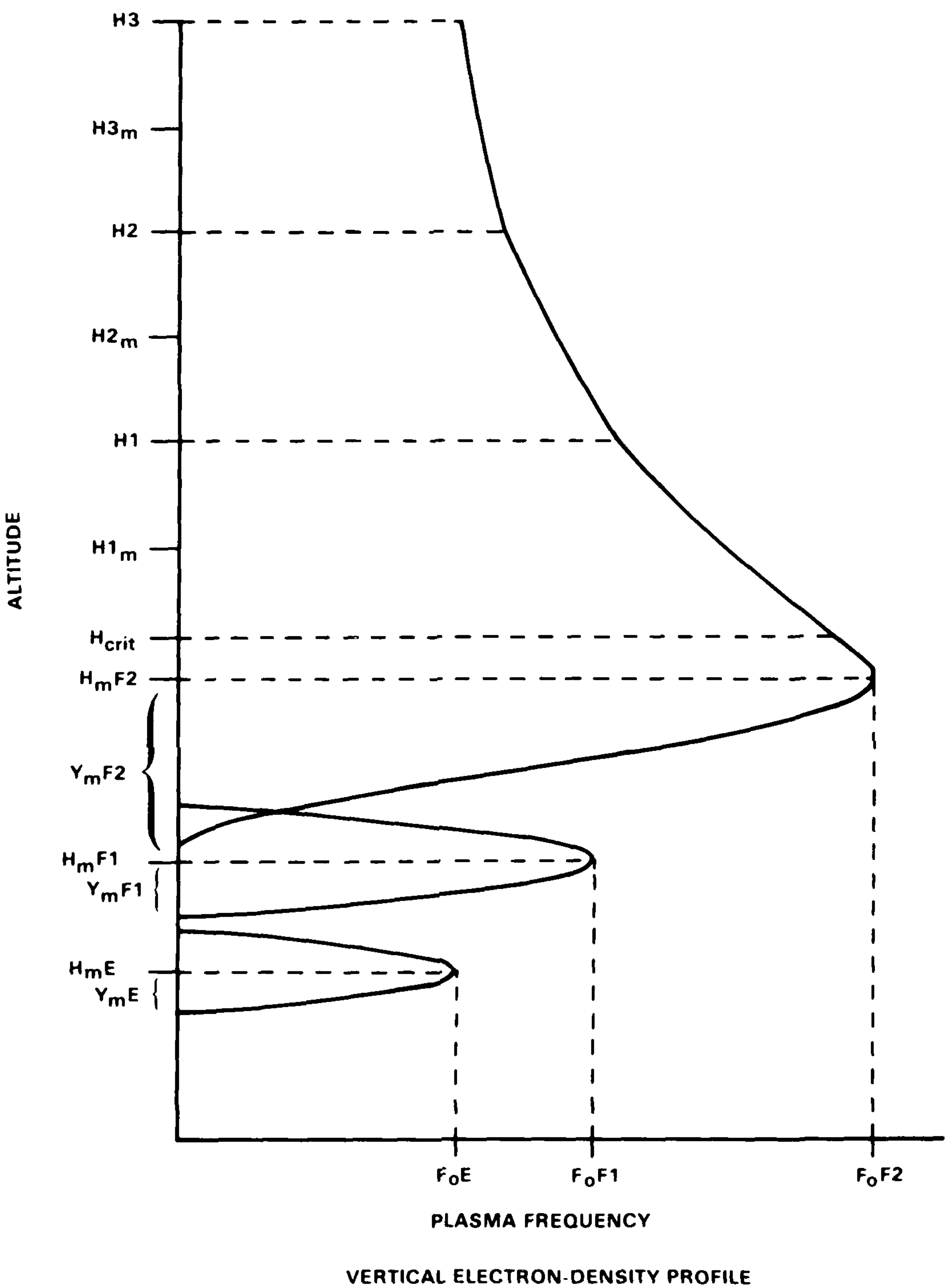

Figure B-2. Vertical Electron Density

K_1, K_2, K_3 - Decay constants for upper F2 region (topside)

H_{crit} - Height at which middle and upper F2 regions match gradients

$H1_m$ - Center of lower topside

$H2_m$ - Center of Middle Topside

$H3_m$ - Center of Upper Topside

7. Geometric and Radar Instrument Delay Distance

a) The sum ($d + d_E$) given for the geometric factor has the electrical delay built in. For SEASAT altimeter processing, geometric distance, D_G, is set to $d + d_E$ and radar instrument delay distance, D_E, is set to zero. The algorithm for d as shown below was obtained from H. Hagar (unpublished data, 1978) at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

$$d(m) = .0254 \left[\left(\frac{1086187 - 434.5\ W_h}{4852.6 - W_h} \right) - 33.6 \right] ,$$

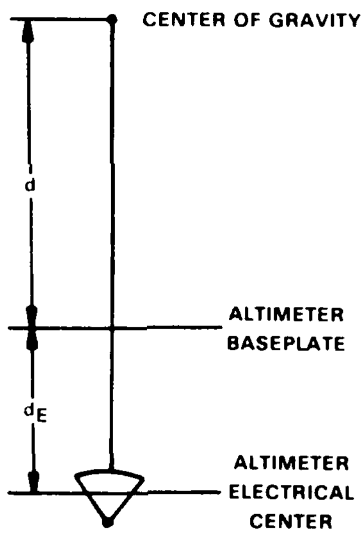

Figure B-4. Geometric and Radar Instrument Delay Distance where

$W_h = 104.5 - W_{hR}$ (lbs)

W_{hR} = pounds of hydrazine remaining

W_{hR} = 89.4 lbs on 13 July 1978

W_{hR} is updated after each major orbit change/momentum wheel dump. These values are given in Table B-1.

Table B-1. Pounds of Hydrazine Remaining, W_{hR}, Year 1978

Maneuver Date	Day	W_{hR}
6/27	178	89.4
8/15	227	87.97
8/18	230	86.05
8/23	235	84.69
8/26	238	75.17
9/10	252	74.62

b) $d_E(m) = 0.47752 + 4.57 \times 10^{-9} \times c,$

where

c = speed of light in meters/second.

c = 299,792,458 m/s (1974 value)

d_E was obtained from J. Lorell (unpublished data, 1978) at the Jet Propulsion Laboratory.

8. Ocean-Tide Correction

The ocean-tide correction was computed by the Schwiderski ocean-tide model (1979), which comprises the seven (7) leading tide constituents; M_2, S_2, N_2, K_2, K_1, O_1, and P_1 of the solid earth, oceans, and the tidal yielding of the solid earth. The total instantaneous ocean tide is computed with 10 cm accuracy. The tide reduction program is based on a one-by-one-degree amplitude and phase tide table, which was hydrodynamically computed by an improved version of the numerical model by W. Zahel (1977).

9. Timing Correction

In an orbit accuracy assessment for SEASAT by Schutz and Tapley (1980) an altimeter time-tag correction of -.079 sec was recommended. This value differs by -.028 sec from the value -.051 sec derived earlier from intersection analysis of SEASAT data at NSWC/DL. The time-tag correction -.051 sec was applied to the altimeter data during reduction to along-track geoid heights and vertical deflections. A time-tag correction was not applied to the altimeter data at FNWC.

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