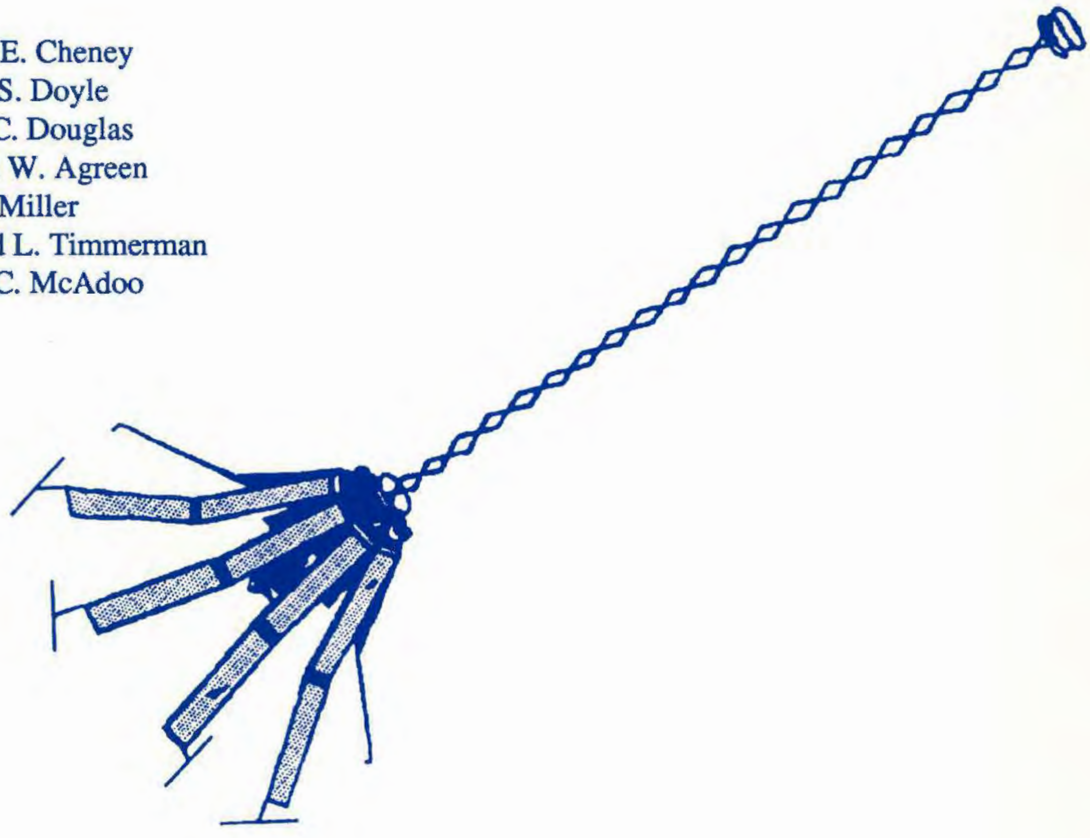
NOAA Manual NOS NGS 7

The Complete Geosat Altimeter GDR Handbook

October 1991

Robert E. Cheney
Nancy S. Doyle
Bruce C. Douglas
Russell W. Agreen
Laury Miller
Edward L. Timmerman
David C. McAdoo



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Service
Rockville, MD

Availability

The Geosat GDRs, together with the handbook, are available through NOAA's National Environmental Satellite Data and Information Service at the following address:

National Oceanographic Data Center
User Services Branch
NOAA/NESDIS E/OC21
Washington, D.C. 20235

Phone: (202) 606-4549
Electronic Mail: OMNET/MAIL mailbox NODC.WDCA

An order form for purchasing the Geosat GDRs can be found at the back of this handbook. Additional information can be obtained from the authors at the following address (after October 1991):

Laboratory for Geosciences
Office of Ocean and Earth Sciences
NOAA/National Ocean Service, N/OES11
Rockville, MD 20852

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

Cover Illustration - The Geosat spacecraft.

NOAA Manual NOS NGS 7

The Complete Geosat Altimeter GDR Handbook

Robert E. Cheney
Nancy S. Doyle
Bruce C. Douglas
Russell W. Agreen
Laury Miller
Edward L. Timmerman
David C. McAdoo

Geodetic Research & Development Laboratory
National Geodetic Survey
Rockville, MD
October 1991

U.S. DEPARTMENT OF COMMERCE
Robert A. Mosbacher, Secretary

National Oceanic and Atmospheric Administration
John A. Knauss, Under Secretary

National Ocean Service
Virginia K. Tippie, Director

Coast and Geodetic Survey
R. Adm. J. Austin Yeager, Director

Contents

Abstract

The U.S. Navy Geosat altimeter mission lasted for nearly 5 years (March 1985 to January 1990) and collected approximately 750 million measurements of sea level, wave height, and wind speed over the global oceans. The raw data from Geosat's exact repeat mission are archived on more than three thousand 9-track tapes at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland. However, most of the information needed for ocean dynamics research is contained in a set of thirty-six geophysical data record (GDR) tapes prepared by NOAA and distributed to users each month during the mission (*Cheney et al.* 1987; 1988; *Doyle et al.* 1989; 1990). The accuracy of these original GDRs has since been significantly improved, primarily by incorporation of new satellite orbits and water vapor corrections (*Cheney et al.* 1991b). This handbook documents the new *T2 GDRs* being distributed by NOAA on six CD ROMs. For completeness, the manual includes a description of the original GDRs and also gives the format for NOAA's classified geodetic mission GDRs, subsets of which have been released to the public.

I. Introduction

From March 1985 until January 1990 the U.S. Navy satellite Geosat generated a new data set with unprecedented spatial and temporal coverage of the global oceans. Designed and built at the Johns Hopkins University Applied Physics Laboratory (JHU APL), Geosat carried a radar altimeter which produced profiles of sea level, wave height, and wind speed along the satellite ground track. Such records have application in many areas of geodesy, ocean dynamics, and global climate research. Experience with Geos-3 and Seasat in the 1970s demonstrated the enormous potential of altimetry, but neither mission provided such complete long-term global coverage.

The acronym Geosat was derived from *geodetic satellite* because its primary mission was to obtain a high-resolution description of the marine geoid. This goal was achieved during the first 18 months, known as the geodetic mission (GM). Because of their military significance, most of the sea level data collected during the GM (March 30, 1985 to September 30, 1986) are classified. However, the satellite orbit was subsequently maneuvered into the exact repeat mission (ERM) orbit, producing sea level profiles along previously released Seasat data tracks, and unclassified operations began on November 8, 1986. The ERM covered 62 complete 17-day repeat cycles, shown by the series of ground track plots in Appendix A, before tape recorder failure in October 1989 terminated the global data set. A limited amount of data was subsequently collected by direct broadcast in the North Atlantic and Gulf of Mexico, but by January 1990 continued degradation of the altimeter output power finally ended the Geosat mission.

Responsibility for producing the ERM geophysical data records (GDRs) for the scientific community was given to NOAA's National Ocean Service (*Cheney et al.* 1987), and these data were distributed during the mission through the NOAA National Oceanographic Data Center. Because these data were based on the operational satellite orbits computed by the Naval Astronautics Group (NAG), we refer to this original release of data as the *NAG GDRs*. A new satellite ephemeris, more precise by an order of magnitude, has since been computed for the ERM by NASA's Goddard Space Flight Center (*Haines et al.* 1990; 1992). We have incorporated these orbits in a new set of *T2 GDRs* (so called because the orbits are based on the GEM-T2 gravity model of *Marsh et al.* 1990). The primary purpose of this handbook is to document the new T2 GDRs, which are being distributed by NOAA in a set of CD-ROMs. In the interest of compatibility, the format and organization of these new data have been changed as little as possible. For completeness, the manual also includes a description of the original NAG GDRs together with the format for the classified GM GDRs, some subsets of which have been released to the public.

In addition to the improved orbit, the T2 GDRs contain other new fields which significantly increase the overall accuracy of the Geosat data. The most important of these is the wet troposphere correction which has been derived from satellite sensors operating during the Geosat mission. From the beginning of the ERM through July 1987, water vapor was retrieved by *Emery et al.* (1990) from the Tiros operational vertical sounder (TOVS) and thereafter by *Wentz* (1989) from the special sensor microwave imager (SSMI). These new water vapor corrections represent a vast improvement (see *Zimbelman and Busalacchi* 1990) over the Fleet Numerical Oceanographic Center (FNOC) value provided in the NAG GDRs. An auxiliary dry trophosphere correction based on the European Center for Medium-Range Weather Forecasting (ECMWF) model is also provided in the new GDRs, enabling substitution for the FNOC value.

Finally, the T2 GDRs incorporate a more accurate geoid model (*Rapp and Pavlis* 1990) and modifications to the ocean tide model.

To illustrate the accuracy attainable using the new water vapor corrections together with the improved T2 orbit, figure 1 displays a set of curves comparing monthly mean sea level measured by the Christmas Island tide gauge with three different Geosat time series computed for the adjacent ocean region. The top analysis is based on the original Geosat NAG GDRs using the FNOC wet troposphere; because of the relatively large uncertainty in the NAG ephemeris, orbit error was removed as a quadratic trend over 10,000-km arcs. The central analysis is the same except the TOVS/SSMI wet correction was substituted for the FNOC value. Finally in the bottom comparison both the TOVS/SSMI correction and the T2 orbit were used; the more accurate ephemeris enabled the orbit error to be removed as a linear, rather than quadratic, trend over the same 10,000-km arcs. As the newer fields are introduced, improvement of the Geosat record is dramatic with the rms difference decreasing from an initial value of 7.0 cm to a final value of 2.9 cm. The low-frequency error evident in the top analysis is evidently a combination of two factors: unmodeled, interannual water vapor anomalies accompanying the 1986-87 El Nino/1988 La Nina and damping of the sea level signal by the quadratic trend (see *Cheney et al.* 1991b for a more complete discussion).

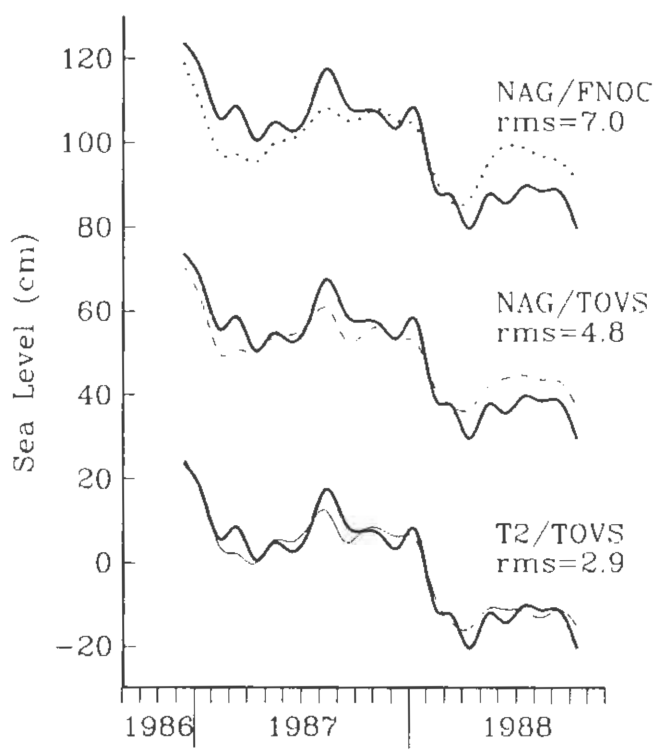


Figure 1. Improvement of Geosat sea level time series using the T2 GDRs near Christmas island in the central equatorial Pacific. Dotted line: NAG/quadratic orbit and FNOC model. Dashed line: NAG/quadratic orbit and TOVS/SSMI model. Thin solid line: T2/linear orbit and TOVS/SSMI model. In each case comparison is made with the Christmas Island tide gauge record (thick solid line). Replacing FNOC with TOVS/SSMI reduces the rms difference from 7.0 to 4.8 cm. Subsequent use of the T2 orbit further reduces the difference to 2.9 cm rms.

II. Geosat Chronology

(a) Geodetic Mission

Geosat was launched on March 12, 1985, and altimeter data collection commenced on March 30, 1985. At the completion of the 18-month geodetic mission on September 30, 1986, the altimeter had accumulated 270 million observations of sea level along 200 million kilometers of the world's oceans with an average cross-track spacing of 4 kilometers. Most of these data are classified and are archived at JHU APL and several U.S. Navy centers.

(b) Transition to the ERM

Beginning on October 1, 1986, Geosat's two onboard thrusters were used to adjust perigee, eccentricity, and the semimajor axis to move into the exact 17-day repeat orbit (*Born et al.* 1988). Over a period of five weeks, 239 separate burns averaging about 100 seconds each were required. Of the 84 pounds of fuel available at the beginning of the mission (no fuel was used during the GM), 45 pounds were expended, and the ERM orbit was achieved on November 7, 1986.

(c) ERM Maneuvers

To compensate for drag and maintain the ERM ground track to within 1 km, only small and relatively infrequent burns were required, consuming 1-2 pounds of fuel each year. Table 1 provides the time and duration of each of the maneuvers. (Except where indicated by parentheses, the effect of the burns was to increase the velocity in the same direction as the flight path.) Burns were paired to reduce attitude disturbances caused by thruster misalignment (less than 1 cm) with respect to the spacecraft center of mass.

During the first year of the ERM, burns were approximately 35 days apart, but with the approach of solar maximum (and therefore maximum atmospheric drag) in 1990-91, burns were required more frequently to maintain collinearity. During the second year of the ERM burns were about 25 days apart, and a dramatic increase in drag during the third year required burns at approximately 12-day intervals. This is also reflected in figure 2 which shows cross-track deviations from the nominal ERM track. Positive values imply eastward deviations. Except for a few isolated instances, collinearity was maintained to within 1 km of the central track. Based on the daily values, the standard deviation of the cross-track separation for the ERM was approximately 0.5 km.

(d) Periods of ERM Data Loss

In addition to data gaps caused by routine attitude excursions (see next section), there were several periods of extreme data loss associated with satellite operations. These are summarized below.

November 19-25, 1987. Geosat carried two momentum wheels to reduce off-nadir attitude angles. Only one wheel was used during the first 2.5 years of the mission, but mechanical degradation was eventually noted, and the second wheel was activated on November 18, 1987. During spin up, spacecraft attitude was disturbed by as much as 7 degrees, and altimeter data collection was reduced for several days thereafter.

August 18-25, 1988. Less than half of the normal number of observations were collected during this time when one of Geosat's batteries was reconditioned. An analysis by *Holdridge (1988)* suggests that poor altimeter performance resulted from regular changing of the satellite's magnetic dipole when the solar arrays were switched between the two onboard batteries. Switching at the orbital frequency for a period of about two weeks had the effect of pumping attitude up to 2-3 degrees in amplitude.

March 16-22, 1989. Severe magnetic storms associated with solar disturbances resulted in a total loss of Geosat data during this time.

October 4, 1989. Collection of global Geosat data ended at this time when the altimeter amplifier was shut down by an automatic protection circuit. Although by-passing this circuit enabled the amplifier to be powered back up in mid-October, failure of both onboard tape recorders limited subsequent data collection to the western North Atlantic using direct broadcast to the JHU APL ground station.

January 5, 1990. Degradation in the output power of the Geosat altimeter resulted in termination of the mission on this date.

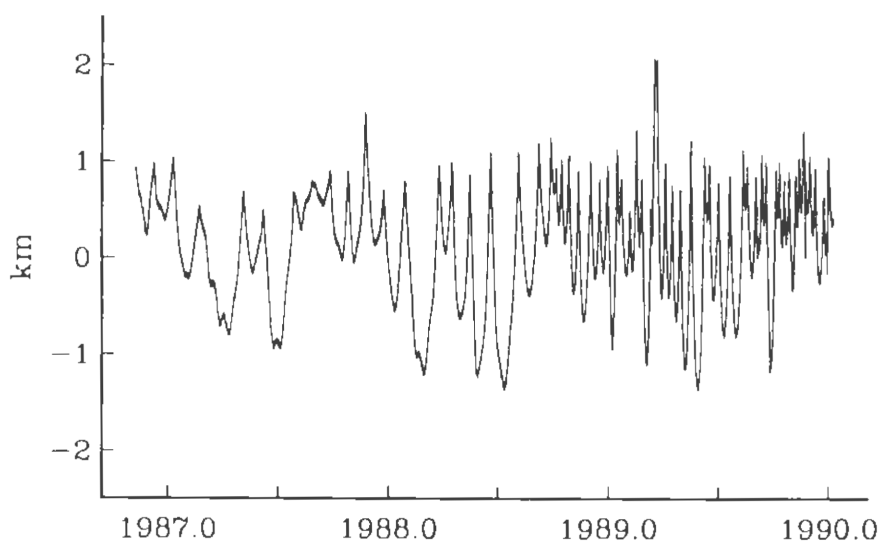


Figure 2. Daily cross-track deviations from the nominal 17-day Geosat ERM track. Positive values indicate eastward deviations. Sharp peaks along the upper limit of the curve correspond to spacecraft maneuvers. The increasing frequency of burns required to maintain collinearity within 1 km is evident. Standard deviation about the central track is 0.5 km.

Table 1. Geosat Maneuvers

Time On	Duration (s)	Time On	Duration (s)
86-341/20:18:07	50	88-135/18:50:00	139
86-341/20:48:20	47	88-135/19:20:00	147
87-007/22:40:51	57	88-146/19:50:01	(25)
87-007/23:11:00	57	88-146/20:20:03	(25)
87-051/10:21:18	41	88-170/12:45:00	147
87-051/10:51:20	50	88-170/13:15:00	139
87-123/17:13:22	74	88-216/15:40:00	123
87-123/17:43:41	64	88-216/16:10:00	123
87-156/18:29:56	74	88-250/18:00:00	147
87-156/19:00:13	66	88-250/18:30:00	147
87-173/19:10:00	(8)	88-270/19:20:16	164
87-173/19:40:00	(16)	88-270/19:50:19	164
87-207/12:30:01	58	88-279/19:45:00	147
87-207/13:00:29	50	88-279/20:15:00	147
87-237/15:17:08	25	88-288/20:10:00	164
87-237/15:47:16	25	88-288/20:40:00	156
87-267/16:14:01	41	88-300/22:00:00	197
87-267/16:43:59	41	88-300/22:30:00	197
87-297/19:08:33	82	88-316/22:00:00	229
87-297/19:39:24	82	88-316/22:30:00	229
87-325/21:27:25	132	88-336/23:35:00	205
87-325/21:56:40	132	88-337/00:05:00	205
87-356/23:37:20	73	88-352/01:50:00	229
87-357/00:08:03	73	88-352/02:20:00	221
88-027/11:15:00	98	88-365/13:00:00	238
88-027/11:45:00	90	88-365/13:30:00	246
88-084/16:54:00	106	89-005/13:15:00	(41)
88-084/17:24:00	106	89-005/13:45:00	(41)
88-105/17:41:00	139	89-014/14:00:00	336
88-105/18:11:00	131	89-014/14:30:00	336

Table 1. Geosat Maneuvers

Time On	Duration (s)	Time On	Duration (s)
89-021/13:15:00	205	89-223/17:40:00	246
89-021/13:45:00	213	89-223/18:10:00	246
89-035/14:30:00	205	89-230/19:00:00	188
89-035/15:00:00	197	89-230/19:30:00	180
89-046/15:00:00	328	89-244/20:10:00	188
89-046/15:30:00	328	89-244/20:40:00	188
89-055/15:30:00	262	89-254/20:00:00	287
89-055/16:00:00	262	89-254/20:30:00	287
89-070/18:00:00	279	89-261/21:15:00	254
89-070/18:30:00	279	89-261/21:45:00	254
89-076/18:00:00	336	89-268/22:45:00	(49)
89-076/18:30:00	336	89-268/23:15:00	(49)
89-080/17:30:00	320	89-277/23:00:00	287
89-080/18:00:00	320	89-277/23:30:00	287
89-094/18:30:00	311	89-283/21:30:00	262
89-094/19:00:00	311	89-283/22:00:00	254
89-105/19:30:00	328	89-291/22:30:00	238
89-105/20:00:00	319	89-291/23:00:00	238
89-119/19:00:00	295	89-299/23:15:00	221
89-119/19:30:00	295	89-299/23:45:00	213
89-136/20:30:00	369	89-311/00:15:00	279
89-136/21:00:00	369	89-311/00:45:00	270
89-159/22:00:00	262	89-317/00:30:00	262
89-159/22:30:00	254	89-317/01:00:00	254
89-167/22:50:00	254	89-324/02:00:00	213
89-167/23:20:00	254	89-324/02:30:00	213
89-182/15:30:00	213	89-327/02:00:00	98
89-182/16:00:00	213	89-327/02:30:00	98
89-201/15:45:00	213	89-334/11:15:00	229
89-201/16:15:00	205	89-334/11:45:00	229

III. GDR Production

Radar altimetry was acquired from Geosat by recording onboard the satellite and dumping the data twice per day to a single ground station at JHU APL (*Jones et al.* 1987). The data were then preprocessed into waveform data records (WDRs) and sensor data records (SDRs). The WDRs (two 9-track tapes per day) contain raw waveform samples used primarily for studies of ice and land. The SDRs (one 9-track tape per day) contain the basic altimeter-measured height, automatic gain control, and significant wave height. WDR and SDR tapes for the entire Geosat mission are archived at JHU APL and their contents are described in the interface control document (*JHU APL* 1985).

Through an agreement with the U.S. Navy, NOAA was given access to the SDRs from both the classified GM and the unclassified ERM. All secret data were processed and analyzed in a dedicated NOAA facility set up at the JHU APL, while all unclassified work was performed at the standard NOAA facilities in Rockville, Maryland. In each case, interim geophysical data records (IGDRs) were first constructed by combining the SDRs with a precise satellite ephemeris, also provided by the Navy. As shown by the flowchart in figure 3, various environmental corrections were then added to construct the final GDRs. Although figure 3 refers specifically to production of the NAG GDRs for the ERM, the same process was used to generate the GM GDRs. Content of the NAG and GM GDRs is discussed in more detail in Sections VI and VII.

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°N). This approach was used to minimize the effect of discontinuities in the NAG ephemeris which occurred at 1-day intervals. Figure 4 shows the total number of records for each day of the complete Geosat mission. Although the SDRs contain approximately 88,000 1-second records per day (one every 0.98 sec), only about two-thirds of these are passed to the final GDR. Data are edited based on SDR flags to remove outliers and segments along which the altimeter was not tracking. Checks are made on the following SDR flags:

Flag	Typical Number of Failures
Unusable flagword	10
Not track mode 1-4	300
Detect flag not set	20,000
ACQ flag not set	15,000
DHa > TDH	25,000
LMax/4 < AGC	5,000
Number typically discarded	35,000

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

Day-to-day changes in the number of records seen in figure 4 are caused primarily by the extra revolution of altimeter data in every third GDR. Some of this *jitter* is also due to daily variations of the satellite ground track with respect to land. The longer period variations are probably due to two effects: (1) varying amounts of data loss caused by large excursions of spacecraft attitude, and (2) data loss caused by seasonal variations of sea ice distribution. In general, the number of observations is high in boreal winter and low in summer, with an average of approximately 50,000 per day. During the final year of the mission, however, more significant data loss occurred because of

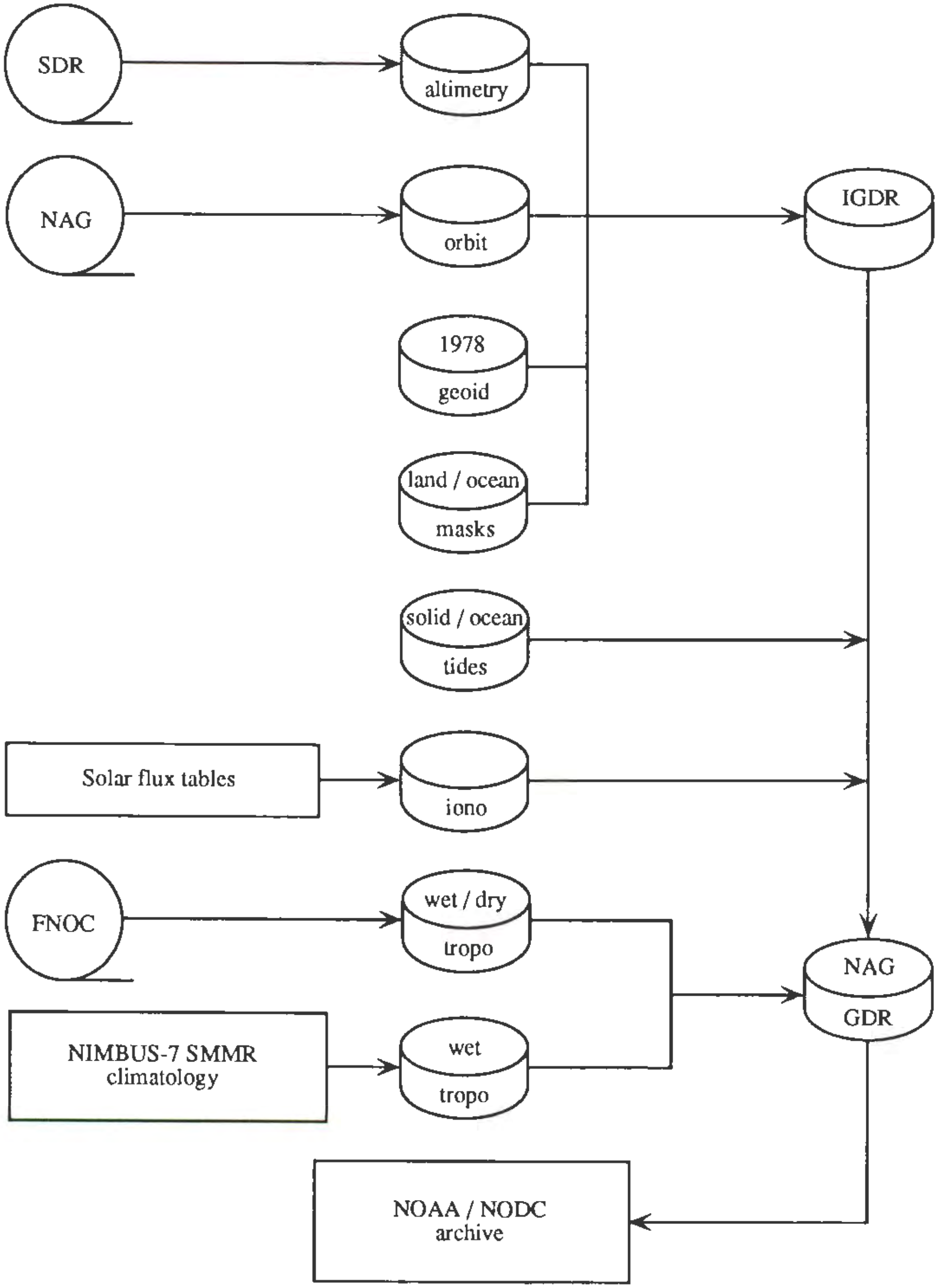


Figure 3. NAG GDR production.

large attitude variations associated with the approach of solar maximum.

The sequence of global ground track plots for each 17-day repeat cycle in the appendix shows the changing areal coverage. (see *Cheney et al.* 1991a for corresponding maps during the GM). Data gaps generally occur in five distinct regions in each hemisphere (cycle 8 is a good example) which change and migrate with time. These gaps are associated with large excursions of spacecraft attitude, as discussed in a subsequent section.

Considerable effort has been made to enhance the accuracy of the original NAG Geosat GDRs, and these improvements have been incorporated in the T2 GDRs. Conversion of the NAG GDRs to the T2 version is shown schematically in figure 5. First the NAG orbit was replaced with the T2 orbit computed at the NASA Goddard Space Flight Center (*Haines et al.* 1990; 1992). All relevant GDR parameters were changed: latitude, longitude, satellite orbit height, 1-second average sea height, and the 10 per second sea heights. Next a new water vapor correction was added based on the TOVS and SSMI observations. Finally the ocean tide and geoid fields were updated, and a new dry troposphere correction was added.

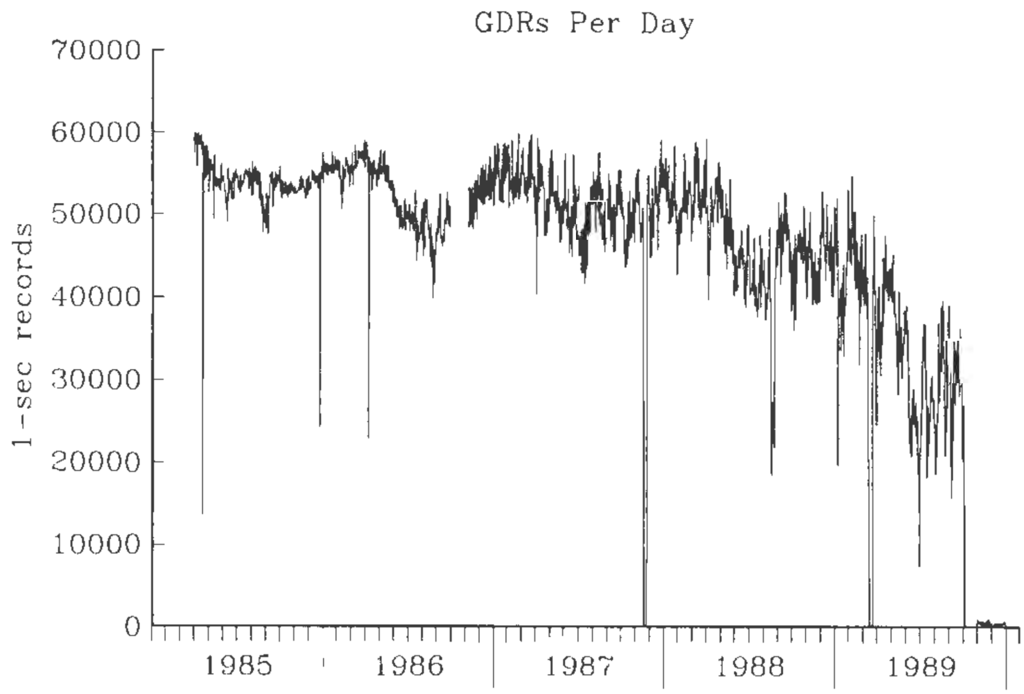


Figure 4. Number of NOAA GDRs for each day of the GM and ERM. The amount of data collected by Geosat decreased dramatically during 1989 due to larger attitude excursions associated with the approach of solar maximum.

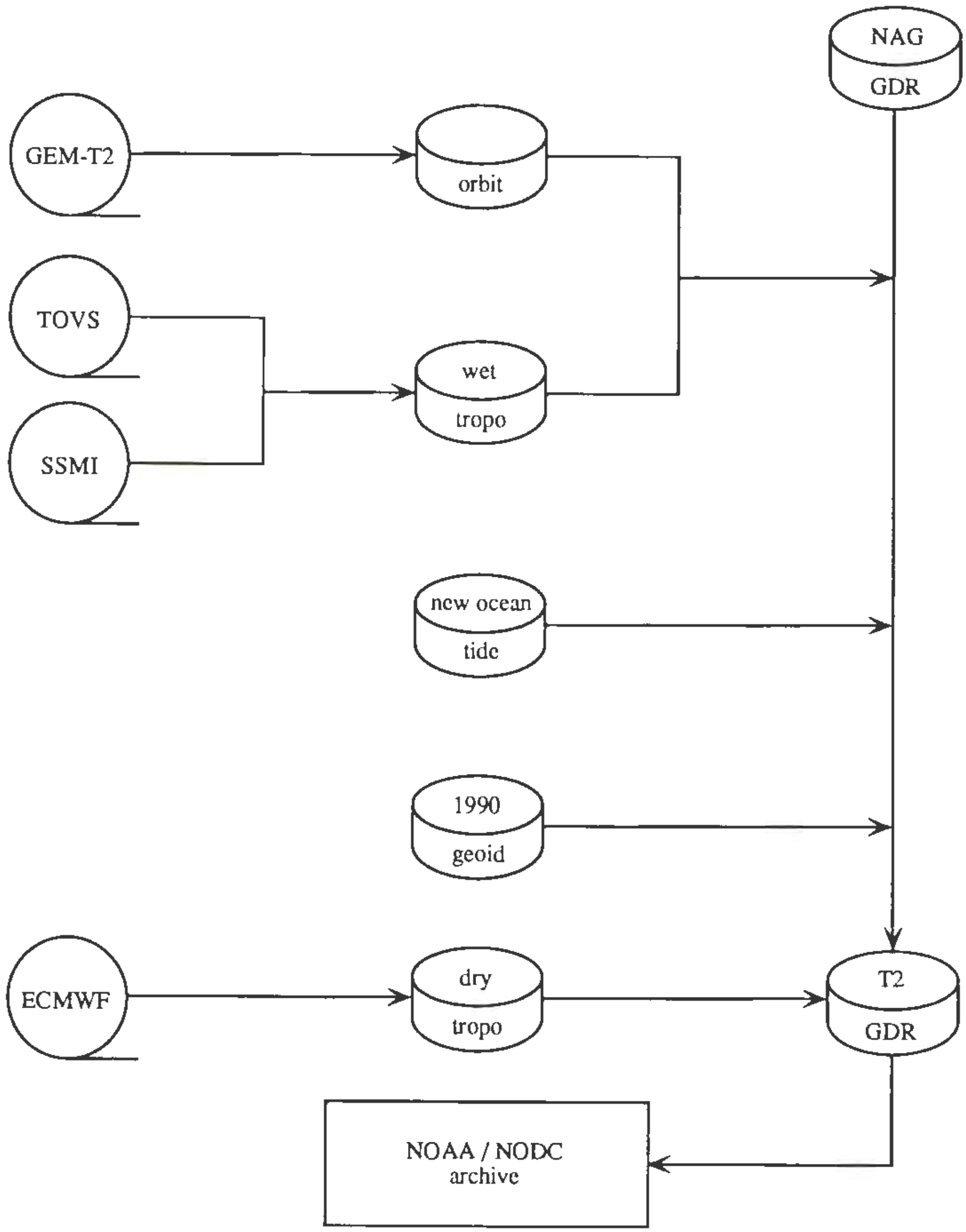


Figure 5. T2 GDR production.

IV. T2 GDR Format and Content

Table 2 summarizes the fields contained in the T2 GDRs. Explanations and applications notes are provided in table 3. One difference between Geosat GDRs and those generally used for Seasat and Geos-3 is 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 per 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 contain fine-scale structure, an interpolation of the data that preserves their inherent precision cannot be made from 1 per second records.

Sample plots of most of the GDR parameters are shown in figure 6 and 7. These data are from the first descending pass on 1986 day 329 which crosses the central Pacific Ocean.

Although the T2 GDRs retain the original NAG GDR structure, with one file per day, the manner in which the new orbits were incorporated requires some explanation. The NAG orbits were computed as a series of 2-day arcs beginning at approximately 1200 UTC with a 12-hour overlap between consecutive arcs. Each NAG GDR file was produced by combining 14 or 15 complete revolutions of data from the SDR with the central day of one particular orbit computation. Thus, each NAG GDR was derived from a different ephemeris, and the resulting orbit discontinuity between consecutive GDRs was always placed at maximum latitude (near 72°N). In contrast, the GEM T2 orbits were computed over much longer arcs, usually 6 days, with a 1-day overlap. Several days of data can thus be treated as one continuous set. A table has been provided on CD ROM #6 showing which groups of T2 GDRs were derived from common orbital arcs and where any orbit discontinuities now exist.

A sample of this table is shown here:

T2 GDR Orbit Epochs

GDR Files (1986)	1985 Seconds		
312 - 316	58,406,700 -	58,844,178	
317 - 321	58,844,179 -	59,272,624	
322 - 326	59,272,625 -	59,707,456	
327 - 331	59,707,457 -	60,135,954	
332 - 335	60,135,955 -	60,480,299	
336 - 341	60,480,300 -	60,984,780	*
341 - 346	60,987,900 -	61,434,113	
347 - 351	61,434,114 -	61,863,082	
352 - 356	61,863,083 -	62,297,431	
357 - 361	62,297,432 -	62,732,159	

(continued on CD ROM #6)

For example, the first 5 days of data from the ERM (1986 GDR files 312 to 316) contain no orbit discontinuities. However, a discontinuity exists between the last record of GDR 316 and the first record of GDR 317.

The asterisk in the table above shows where the discontinuity corresponds to a gap in the ephemeris because of an orbit maneuver. This represents another difference between the NAG and T2 orbits. The NAG orbits were computed without regard for maneuvers, whereas the T2 arcs stop just before a burn, and a new arc begins after the burn, imposing a gap of approximately 3000 seconds, or half of one revolution. These orbit-maneuver discontinuities occur in the middle of the GDR files, and no attempt was made to place the endpoints at either maximum or minimum latitude. However, investigators analyzing the Geosat data as separate arcs of one-half revolution or less can essentially ignore the issue of orbit discontinuities.

Table 2. T2 GDR Format

Item	*Parameter*	*Units*	*Bytes*
1	UTC	sec	4
2	UTC continued	microsec	4
3	Latitude	microdeg	4
4	Longitude	microdeg	4
5	Orbit (GEM T2)	mm	4
6	H	cm	2
7	σ_H	cm	2
8	Geoid	cm	2
9	H (1)	cm	2
10	H (2)	cm	2
.	.	.	.
18	H (10)	cm	2
19	SWH	cm	2
20	σ_{SWH}	cm	2
21	σ_0	0.01 db	2
22	AGC	0.01 db	2
23	σ_{AGC}	0.01 db	2
24	Flags		2
25	H offset	m	2
26	Solid Tide	mm	2
27	Ocean Tide	mm	2
28	Wet (FNOC)	mm	2
29	Wet (SMMR)	mm	2
30	Dry (FNOC)	mm	2
31	Iono	mm	2
32	Wet (TOVS/SSMI)	mm	2
33	Dry (ECMWF)	mm	2
34	Attitude	0.01 deg	2
		Total	78

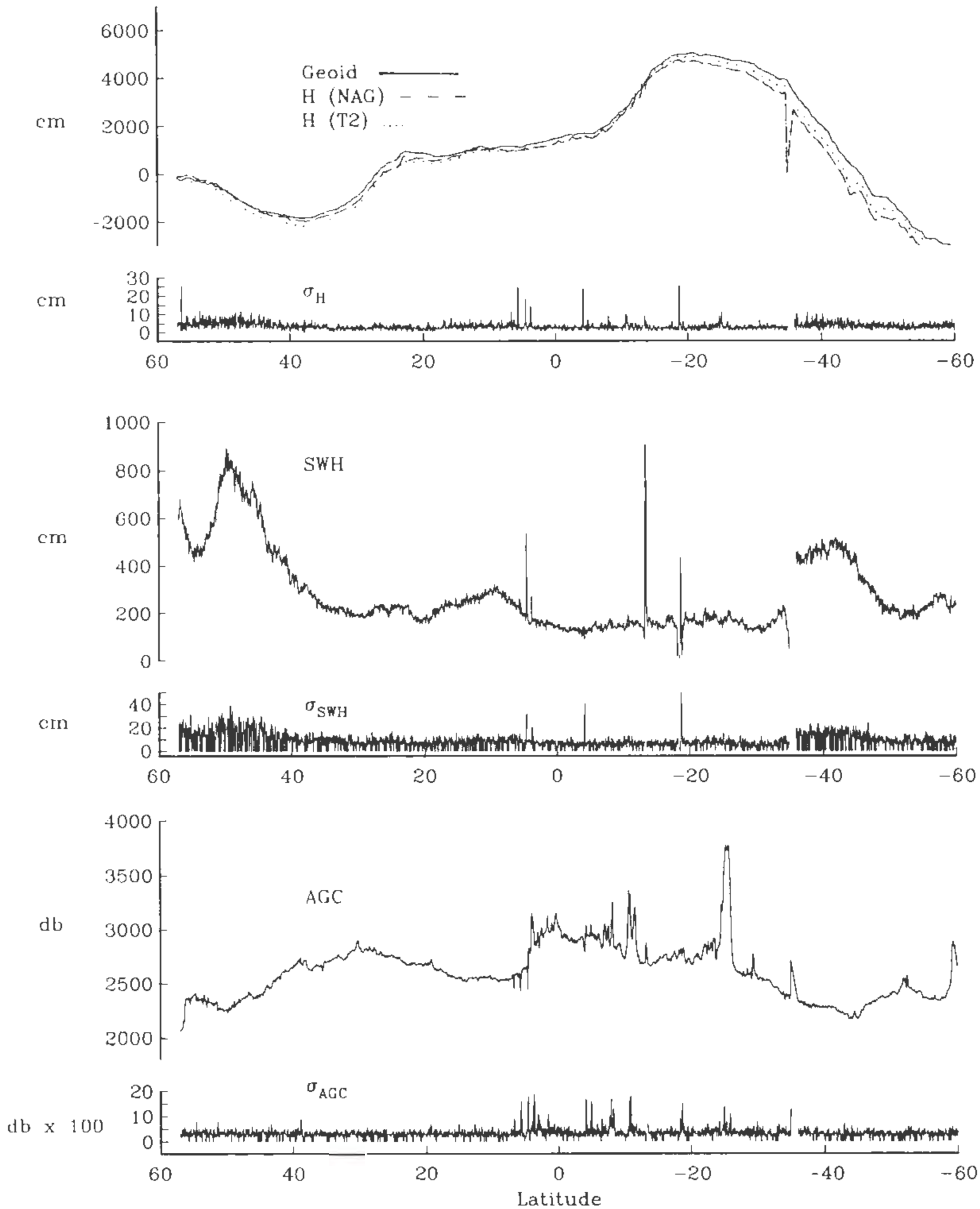


Figure 6. Various T2 GDR parameters as a function of latitude for the first descending pass on 1986 day 329 (central Pacific). The corresponding NAG sea height profile is also shown.

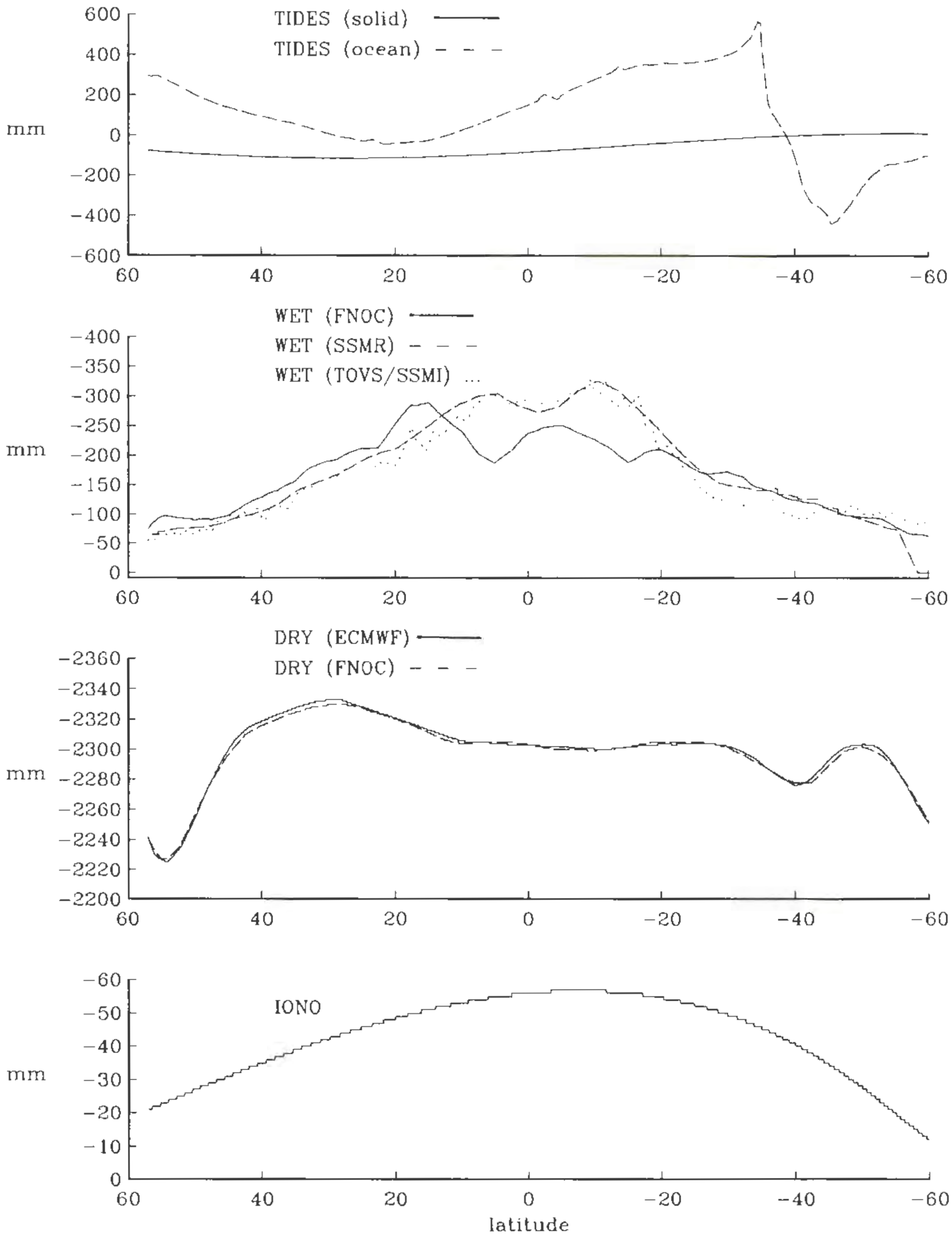


Figure 7. Various T2 GDR parameters as a function of latitude for the first descending pass on 1986 day 329 (central Pacific).

Table 3. T2 GDR Definitions

Item	*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 continued	Time continued in microseconds. Addition of a leap second was required at the end of 1987. Leap seconds present difficulties in altimeter data sets because the satellite is technically at two different locations at the same time on one particular arc. We have chosen to simply delete a short segment of data so that the leap second occurs between two different orbital arcs. Accordingly, the GDR for 1987 day 365 was truncated on an ascending arc 1 second before the end of the day. The GDR for 1988 day 1 begins 2425 seconds into the day on a descending arc.
3	Latitude	North latitude (negative for south).
4	Longitude	East longitude.
5	Orbit	Satellite height above the Global Reference System 1980 (GRS 80) ellipsoid, where the ellipsoid is defined by: $a = 6378.137$ km $f = 1/298.257$ The satellite orbit was computed by the NASA Goddard Space Flight Center using the GEM T2 geoid model and coordinate system *(Haines et al., 1992)*. Orbits are computed for 6-day arcs with one or two day overlap of consecutive orbit computations. Ephemeris is at 1-minute time intervals and is evaluated at approximately 0.1-second intervals with a 9-point Lagrangian interpolator for use with 10 per second altimeter range measurements.
6	H	1-second average sea surface height above the reference ellipsoid $H = 0.1\ (\text{Orbit}) - \text{Alt}$ where Alt = altimeter height in centimeters between the satellite and the sea surface (after correction for FM crossstalk, spacecraft center-of-gravity, pre-launch calibration, and attitude/SWH bias *(JHU APL, 1985)*.

Table 3. T2 GDR Definitions (continued)

Item	*Parameter*	*Definition*
6	(H continued)	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 per second data, and the largest approximately standardized residual is tested against a tau distribution at the 95 percent confidence (*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 σ_H. If less than six good points are available, H and σ_H are set = 32767. NOTE: H is NOT corrected for wet and dry troposphere, ionosphere, and tides. These corrections may be incorporated by the formula: H (corrected) = H - 0.1 (Tides + Wet + Dry + Iono) where Tides = (Solid Tide + Ocean Tide) Wet = TOVS/SSMI (preferred), SMMR, or FNOC Dry = ECMWF (preferred) or FNOC The sign of the Wet, Dry, and Iono corrections is always negative in the GDR, whereas the Tide corrections may be positive or negative. Corrections for sea-state bias (often a percentage of SWH) and inverse barometer (see Item 33 below) are also usually required, but these are left to the investigator.
7	σ_H	Standard deviation from a linear fit to the 10 per second sea height values used in computing H. Only non-rejected values are used to compute σ_H with a minimum of six good points required.
8	Geoid	Geoid height above GRS 80 ellipsoid. Value computed with bilinear interpolation using 1-degree geoid height estimates computed from *Rapp and Pavlis* (1990).

Table 3. T2 GDR Definitions (continued)

Item	*Parameter*	*Definition*
9-18	H(1)-H(10)	Sea height values at 10 per second rate used to compute H. To time tag the ten height values, use: time(i) = time of record + 0.97992165 (i/10 - 0.55), i = 1,2,...,10
19	SWH	Significant wave height determined onboard the spacecraft at the rate of 10 per second. SWH is an average 1-second value determined from the 10 per second data by the method described in item 6. A correction has been applied for attitude/SWH bias *(JHU APL, 1985: p.73)*
20	σ_{SWH}	Standard deviation of the 10 per second wave height values used in computing SWH. Only non-rejected values are used to compute σ_{SWH} with a minimum of six good points required.
21	σ_0	Backscatter coefficient computed from AGC, applying corrections for satellite height, receiver temperature, attitude/SWH effect, onboard calibration, and pre-launch calibration *(JHU APL, 1985: p. 73)*.
22	AGC	Automatic gain control determined onboard the spacecraft at a rate of 10 per second. This parameter indicates signal strength at the altimeter receiver. AGC is an average 1-second value determined from the 10 per second data by the method described in item 6.
23	σ_{AGC}	Standard deviation of the 10 per second automatic gain control values used in computing AGC. Only non-rejected values are used to compute σ_{AGC} with a minimum of six good points required.
24	Flags	Flag bits are 0-15, right to left: bit 0 = 1 — if over water based on a 1/12 degree mask *(Shum et al., 1987)* bit 1 = 1 — if over water > approximately 2000 m depth bit 2 = 1 — if either dh(SWH/ATT) or dh(FM) out of normal range. The height bias, dh(SWH/ATT), results from a combination of SWH and Attitude. This correction has been applied to values of H and H(1)-H(10). The dh(SWH/ATT) value was given in the SDR, but is not provided in the GDR.

Table 3. T2 GDR Definitions (continued)

Item	*Parameter*	*Definition*	
24	(Flags continued)	bit 3 = 1	if any of the 10/second heights set to 32767 cm
		bit 4 = 1	if VATT is extrapolated > 4 minutes (for explanation of VATT, a parameter used to compute ATT, see *JHU APL, 1985: pp. 24-25*)
		bit 5 = 1	if VATT estimated (value not available)
		bit 6 = 1	if VATT estimate used less than 60 raw sample
		bit 7	not used
		bit 8	not used
		bit 9	not used
		bit 10	not used
		bit 11	not used
		bit 12 = 1	if FNOC interpolation > 12 hours
		bit 13 = 1	if solar flux value < 75 or > 230 units (see Figure 10)
		bit 14 = 0	not used
		bit 15 = 1	not used
25	H Offset	Offset 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 per second height values. This bias has been subtracted from each of the land heights H and H(1)-H(10). Thus to recover heights over land, H Offset must be added to all H values for which the land flag is zero. H (corrected) = H + 100 (H Offset) NOTE: H Offset = 0 for altimeter heights over water.	
26	Solid Tide	Solid earth tide correction to H. Based on *Cartwright and Tayler (1981)* and *Cartwright and Edden (1973)*. The solid tide height is determined at 1-second intervals from computations of the tide generating potential and its gradient at 30-second intervals along the satellite ground track.	

Item	Parameter	Definition
27	Ocean Tide	Surface ocean tide correction to H. 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). From suggestions made by P.L. Woodworth of Proudman Oceanographic Laboratory (POL), two modifications were made. First, the Q1 model constituent was changed to include a term for the mean longitude of lunar perigee, P_0. This term was accidentally omitted from table 1 of *Schwiderski and Szeto (1981)*. Second, nodal variation terms were added to all 11 model constituents. In order to gauge the overall effect of these changes on the GDR tidal corrections, a before/after comparison was made with respect to the POL implementation of the Schwiderski tide model. Before making these changes, the GDR and POL tide programs differed by approximately 1.8 cm rms over the open ocean, and 0.3 cm afterwards.
28	Wet (FNOC)	Wet troposphere correction to H based on the Fleet Numerical Oceanographic Center (FNOC) model. Although this was the primary water vapor correction in the NAG GDRs, the more accurate TOVS/SSMI field (item 32) should be used (see Section IX). Surface values of air temperature and water vapor pressure were interpolated along the Geosat track at 1-sec intervals from FNOC model (2.5° global grids at 12-hour intervals). Then, $\text{Wet (FNOC)} = -2.277\ (0.05 + (1255/(T + 273.16)))\ (e)$ where T = surface atmospheric temperature in °C e = surface water vapor pressure in mbar
29	Wet (SMMR)	Auxiliary wet troposphere correction to H based on data from the NIMBUS 7 scanning multichannel microwave radiometer, or SMMR. This correction may be used in lieu of Wet (TOVS/SSMI) correction. Values of vertically integrated atmospheric water vapor are interpolated along the Geosat track at 1-second intervals from a climatic monthly mean SMMR data set *(Prabhakara et al., 1985)*. The SMMR data set is in the form of a 3° latitude by 5° longitude global grid of monthly averages for the years 1979-81. Then, $\text{Wet (SMMR)} = -6.36\ W$ where W = vertically integrated water vapor in gm/cm^2

Table 3. T2 GDR Definitions (continued)

Item	*Parameter*	*Definition*
30	Dry (FNOC)	Dry troposphere correction to H from the FNOC model as discussed in item 28. Because the model was changed in January 1988 *(Barker et al., 1988)*, we recommend that the Dry (ECMWF) be used instead (see item 33).
31	Iono	Ionosphere correction to altimeter surface height. Based on the *Klobuchar (1987)* 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 (see Section X).
32	Wet (TOVS/SSMI)	Wet troposphere correction to H based on satellite radiometer measurements from the TIROS operational vertical sounder (TOVS; *Emery et al., 1990*) and the special sensor microwave imager (SSMI; *Wentz, 1989*). TOVS was incorporated from the beginning of the Geosat mission through the end of 1987 day 189 (July 8, 1987). SSMI was used for the remainder of the Geosat mission. TOVS/SSMI values of the integrated tropospheric water vapor content were interpolated to the Geosat groundtrack at 1-second intervals and converted to altimeter path length corrections using the relation $\text{Wet (TOVS/SSMI)} = -6.36\ W$ where W = vertically integrated water vapor in gm/cm^2 A bias was found to exist between the globally-averaged TOVS and SSMI water vapor data (see Section IX). We recommend that 1.4 cm be subtracted from all TOVS/SSMI GDR values prior to July 9, 1987. Because all corrections have negative sign, this would increase the magnitude of the wet tropo value.

Item	*Parameter*	*Definition*
33	Dry (ECMWF)	Dry troposphere correction compensating for the altimeter travel time delay caused by air molecules. Based on the operational model of the European Center for Medium-range Weather Forecasting. Although this correction is recommended rather than Dry (FNOC) in item 30, the two models are quite similar. The sample profile in Figure 7 shows that the largest difference between ECMWF and FNOC is only about 5 mm. Similarly, global averages computed for each ERM cycle show differences of only 1 mm or less. Values along the satellite track are interpolated at 1-second intervals from the ECMWF model output. The dry correction is then Dry (ECMWF) = - 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. The time scale on which the ocean responds is not well understood and is a subject of ongoing research (e.g. *VanDam, 1991*). 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 (ECMWF) correction: P = Dry (ECMWF) / (- 2.277)(1 + (0.0026 cos (2 Latitude))) where P = surface atmospheric pressure in mbar The inverse barometer correction in millimeters is then: - 9.948 (P - 1013.3) To apply this correction, it should be subtracted from altimeter sea height, H.
34	Attitude	Spacecraft off-nadir orientation angle estimated by ground processing of the return waveform trailing edge.

V. How To Use the CD-ROMs

Each CD-ROM contains several introductory files. The following is excerpted from the READ-ME file:

File 1. READ-ME (General information).

File 2. GDR-FORM (T2 GDR contents; see Table 2 of this handbook). The Geosat T2 data are stored in files, each of which contains one day of measurements. The naming convention used for the data files is:

DAY_###.YY

where ### is the Julian day number and yy is the year.

Data in these files are exactly the same as the binary, "Hewlett-Packard (HP) format" GDRs distributed by NODC on 9-track, non-labelled, binary magnetic tapes. The only difference is the storage/transfer medium. 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. 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.

File 3: EQC-TABL (Equator Crossing Table). The ERM ground track repeated approximately every 17.0505 days (1,473,163 seconds), the time which defines one repeat cycle. During each cycle the satellite completed 244 revolutions and crossed the equator 488 times. This table provides the time and longitude of each equator crossing for the specific data included on the disc. Entries are in chronological order with time in microseconds relative to January 1, 1985 and longitude in microdegrees east. This information may be used to identify Geosat passes having the same ground track.

Occasional gaps in the equator crossing table correspond to times when the Geosat thrusters were fired to maintain the collinear ground track. Because accurate orbits cannot be computed during these events, gaps of approximately one-half revolution have been imposed in the T2 GDRs at the satellite maneuver times. During the first year of the ERM, maneuvers were approximately 35 days apart, whereas in the second year the interval was about 25 days. Increased atmospheric drag in the third year required the thrusters to be fired at approximately 12-day intervals.

File 4. VAX-CONV (HP to VAX conversion software). For "VAX format" users, a FORTRAN program (GESATRD2) is included on each CD-ROM to convert the HP formatted binary data to VAX formatted binary data. This program should be uploaded to the VAX computer, compiled, and linked. The GESATRD2 software will prompt for input and output file names.

File 5. EQC-TABL.ALL (Found on Disc #6 only). The equator crossing table for the data in all 6 discs is provided.

File 6. ORB-EPOC (Found on Disc #6 only). This table shows which groups of T2 GDRs were derived from common orbital arcs and where any orbit discontinuities exist.

VI. NAG GDR Content

Separate Ocean and Land/Ice NAG GDRs were produced for the ERM, however, only the ocean data were upgraded into T2 GDRs. Whereas it is recommended that the T2 GDRs be used for all ocean applications, the original NAG Land/Ice GDRs must still be used over non-ocean surfaces. Unless noted below, the format and content of the NAG GDRs are as described in Tables 2 and 3.

(a) Ocean GDRs

This section briefly discusses those fields which were changed when the NAG GDRs were converted to the T2 GDRs.

Items 3 and 4. Latitude and Longitude - The NAG ephemeris was interpolated to determine the precise position at the time of the record. The difference between the NAG and T2 positions was typically 9 m rms cross-track and 14 m rms along-track.

Item 5. Orbit - Satellite height above the reference ellipsoid at the time of the record based on the NAG ephemeris. The World Geodetic System 1972 (WGS-72) coordinate system was used, where the reference ellipsoid was defined as:

$$a = 6378.137 \text{ km}$$

$$f = 1/298.257223563$$

The Goddard Earth Model 10 (GEM 10; *Lerch et al., 1979*) was also used rather than the more accurate GEM T2 model. The difference between the NAG and T2 satellite heights was typically 4 m rms.

Item 6. H - Based on the NAG ephemeris, 1-second average sea surface height above the reference ellipsoid derived from the 10 per second heights. The same compression algorithm was used for both NAG and T2 GDRs.

Item 8. Geoid - Geoid height above the GRS 80 ellipsoid computed from the model of Rapp (1978). For NAG GDRs prior to 1988 Day 203, an error in the interpolation routine caused fictitious ripples in the geoid profiles.

Items 9-18. H(1)-H(10) - Based on the NAG ephemeris, 10 per second sea surface height above the reference ellipsoid used to compute H.

Item 26. Ocean Tide - The two modifications discussed in Table 3, Item 27, were made to all NAG GDRs from 1988 Day 297 onward.

Item 32. dh(SWH/ATT) - Height bias in mm resulting from a combination of SWH and attitude. This correction was applied to values of H and H(1)-H(10) for both NAG and T2 GDRs, but should not be confused with the *sea state bias* or *EM bias* correction. This parameter was replaced by Wet (TOVS/SSMI) in the T2 GDRs.

Item 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) for both NAG and T2 GDRs. This parameter was replaced by Dry (ECMWF) in the T2 GDRs.

(b) Land/Ice GDRs

During production of the NAG ocean GDRs editing was performed based on SDR flags. This resulted 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 waveform data records (WDRs). In order to create a comprehensive archive, these discarded records were collected in separate Land/Ice GDRs. These consist of all records over land (regardless of data quality) plus all records over water which failed one of the seven tests summarized in section III.

Structure of the Land/Ice GDRs is the same as the NAG ocean GDRs, but additional information is provided in the flag field to indicate which of the data quality tests failed. Changes to the GDR flags are provided below:

Bit Location	Definition for flag = 1	Ocean GDR Value
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

VII. GM GDR Content

Geosat altimeter data collected during the 18-month Geodetic Mission (GM), April 1985 to September 1986, are classified because of military applications related to knowledge of the marine geoid. Two different sets of GM GDRs exist: those produced by the Naval Surface Weapons Center (*West* 1986), and those produced by NOAA. Here we discuss only the NOAA data set.

The NOAA GM GDRs were produced in a secure computer facility at JHU APL for sea level variability studies (*Cheney et al.* 1986). Several unclassified subsets of these data are available: global wind speed and wave height (*Dobson et al.* 1988), crossover differences (*Cheney et al.* 1991a), and most recently, GDRs for various geographic regions. An example of one GDR subset is the Southern Ocean area from 60°S to 72°S (*Marks and McAdoo* 1991).

In order to produce a dense map of the marine geoid, the GM was based on a 23-day near repeat orbit which was permitted to drift, ultimately producing a tightly spaced ground track pattern. At the end of the 18 months, the spacing between adjacent tracks at the equator was approximately 5 km, and at 60° latitude only 2 or 3 km. Ground track maps for each 23 days can be found in (*Cheney et al.* 1991a).

The NOAA GDRs are based on a classified satellite ephemeris produced by the Naval Surface Weapons Center (NSWC). Orbits were computed in discrete 2.3-day time spans with a 2-revolution overlap between consecutive orbits. A continuous ephemeris for the GM was then produced using a cosine smoother to eliminate discontinuities (*West* 1986). This is in contrast to the NAG orbits for the ERM which contained discontinuities at 1-day intervals. As a result, the ERM GDR files contain either 14 or 15 complete revolutions of data to place the discontinuities at maximum latitude, whereas the GM GDRs simply contain 24 hours of data (approximately 14.3 revolutions) in each file since there are no orbit discontinuities to take into account. Otherwise the structure of the GM GDRs is similar to the ERM GDRs.

Except as noted below, the format and content of the GM GDRs are as described in Tables 2 and 3.

Item 5. Orbit - Satellite height above the reference ellipsoid at the time of the record based on the NSWC ephemeris. The World Geodetic System 1984 (WGS-84) gravity model and coordinate system were used, where the reference ellipsoid was defined as:

$$a = 6378.137 \text{ km}$$

$$f = 1/298.257223563$$

Item 6. (not used) - Set to 32767. 1-second average H is not provided in the GM GDRs, but can be derived from the 10 per second heights.

Item 7. (not used) - Set to 32767. σ_H is not provided in the GM GDRs, but can be derived from the 10 per second heights.

Item 8. Geoid - Geoid height above the ellipsoid computed from the model of Rapp (1978).

Item 20. (not used) - Set to 32767. σ_{SWH} is not provided in the GM GDRs.

Item 22. (not used) - Set to 32767. AGC is not provided in the GM GDRs.

Item 23. (not used) - Set to 32767. σ_{AGC} is not provided in the GM GDRs.

Item 24. Flags - The land/water flag (bit 0) was based on a 1-degree mask, rather than a 1/12 degree mask. Bits 4, 5, 6, and 12 were not used.

Item 26. Ocean Tide - The two modifications discussed in Table 3, Item 27, were not made.

Item 32. dh(SWH/ATT) - Height bias in mm resulting from a combination of SWH and attitude. This correction was applied to values of H and H(1)-H(10), but should not be confused with the *sea state bias* or *EM bias* correction.

Item 33. dh(FM) - Height bias in mm resulting from linear compression of the altimeter pulse. This correction has been applied to values of H and H(1)-H(10).

VIII. Orbit Precision

Geosat ephemeris computations have been performed by various groups based on tracking of the onboard Doppler beacon. The precision of these orbits varies depending on the number and distribution of the tracking stations and the force models employed (geoid, drag, solar radiation pressure, etc.). The altimeter data itself has also been used to supplement the tracking data. In this section we summarize the precision of the most commonly used Geosat orbits. (Note that by precision, we mean the rms variability of the computed orbits as measured by altimeter crossover or collinear differences. Geosat did not carry a laser reflector for absolute calibration; the values provided here should not necessarily be interpreted as accuracy in an absolute sense.)

(a) NSWC Orbits for the GM

Tracking during the GM was performed by the global network of approximately 46 stations operated by the U.S. Defense Mapping Agency (DMA). These data have not been released to the general research community, and only one ephemeris was known to have been produced. Ephemeris computations for GM were performed at the Naval Surface Weapons Center (NSWC). The WGS-84 gravity model was used to compute precise orbits for Geosat in 2-day time spans. A continuous ephemeris was generated by overlapping consecutive spans by two revolutions and then using a cosine smoother to eliminate discontinuities (*West, 1986*). The excellent global coverage provided by the DMA network together with the relatively low atmospheric drag during 1985-86 resulted in an ephemeris with a precision of approximately 60 cm (see *Cheney et al.* 1991a, Figure 5).

(b) NSWC Orbits for the ERM

Tracking by the full DMA network continued throughout the ERM, and classified orbits were computed by NSWC in the same manner as for the GM. The precision of these orbits remained at approximately 60 cm. In constructing the Geosat crossover difference records (*Cheney et al.* 1991a), the NSWC ephemeris was used to produce a consistent set of data covering the 1.5-year GM plus the first year of the ERM. This enables computation of sea level time series spanning the gap between the GM and ERM.

Limited subsets of the DMA tracking data have been released to civilian agencies. For example, 80 days of data from early 1987 were used by *Haines et al.* (1990) and *Shum et al.* (1990) for station coordinate studies and refinement of precise orbit determination techniques.

(c) NAG Orbits for the ERM

The original satellite ephemeris used to produce the Geosat ERM GDRs was computed by NAG from Doppler tracking from only four U.S. sites in Maine, Minnesota, California, and Hawaii. Together with the Goddard Earth Model-10 geopotential field (*Lerch et al.* 1979), this resulted in a satellite orbit with an estimated radial uncertainty of about 3 m rms (*Born et al.* 1988). Ephemerides were in the form of separate 2-day arcs with 12 hours overlapping between consecutive arcs; they were not joined together, as was done by NSWC, so that discontinuities existed between ephemeris files. Considering the operational nature of the NAG orbit, the results must be considered exceptional, and the NAG orbit has not precluded important scientific results being obtained from Geosat data (*Douglas and Cheney* 1990).

(d) T2 Orbits

In the new release of Geosat GDRs on CD-ROM, we have used the ephemeris computed by *Haines et al. (1990)* based on the GEM-T2 geopotential model of *Marsh et al. (1990)* and Doppler data from an augmented network of stations. In addition to the four U.S. tracking stations used by NAG, Doppler data were obtained from one site in Belgium, two Canadian stations, and three stations operated by France in French Guiana, Tahiti, and Kergulen Island. Figure 8 shows the difference between the NAG and T2 orbits for a 1-day span: rms differences are 2.5 m radial, 8.8 m cross-track, and 12.1 m along-track. The dominant frequency is once per revolution, with the error primarily attributable to the NAG orbit, but uncertainties in both ephemerides also cause modulations at other frequencies. The along-track component of the satellite position contains lower-frequency errors of almost 40 m, probably due to uncertainties in modeling non-gravitational forces such as drag. In the T2 GDRs, latitudes and longitudes (in addition to the radial heights) were therefore revised using the more accurate T2 ground track.

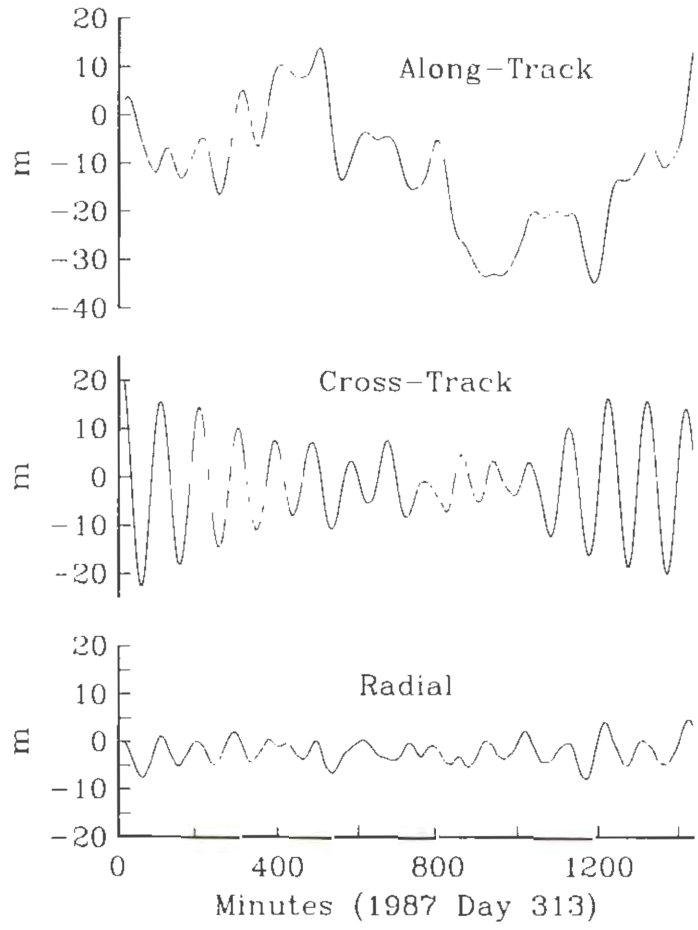


Figure 8. Difference between the NAG and T2 Geosat orbits for a 1-day period separated into radial, cross-track, and along-track components. Most of the difference is attributable to uncertainty in the NAG orbit, which has a precision of approximately 3 m compared to 15 cm for the T2 orbit.

As a measure of the T2 orbit precision, we use collinear differences, averaged globally, for each of the 62 complete cycles relative to cycle 2 (Figure 9a). For the first half of the ERM, the rms differences are 25-35 cm, implying orbit precision of 10-25 cm (dividing by the square root of two.) Thereafter, the collinear differences grow, reaching levels of 60-80 cm during 1989 (implying orbit precision of approximately 40-60 cm). As shown in Figure 9b, there is a significant correlation (r = 0.7) between orbit error and solar flux, indicating that the increased orbit error is due to the additional, unmodelled atmospheric drag accompanying the approach of solar maximum.

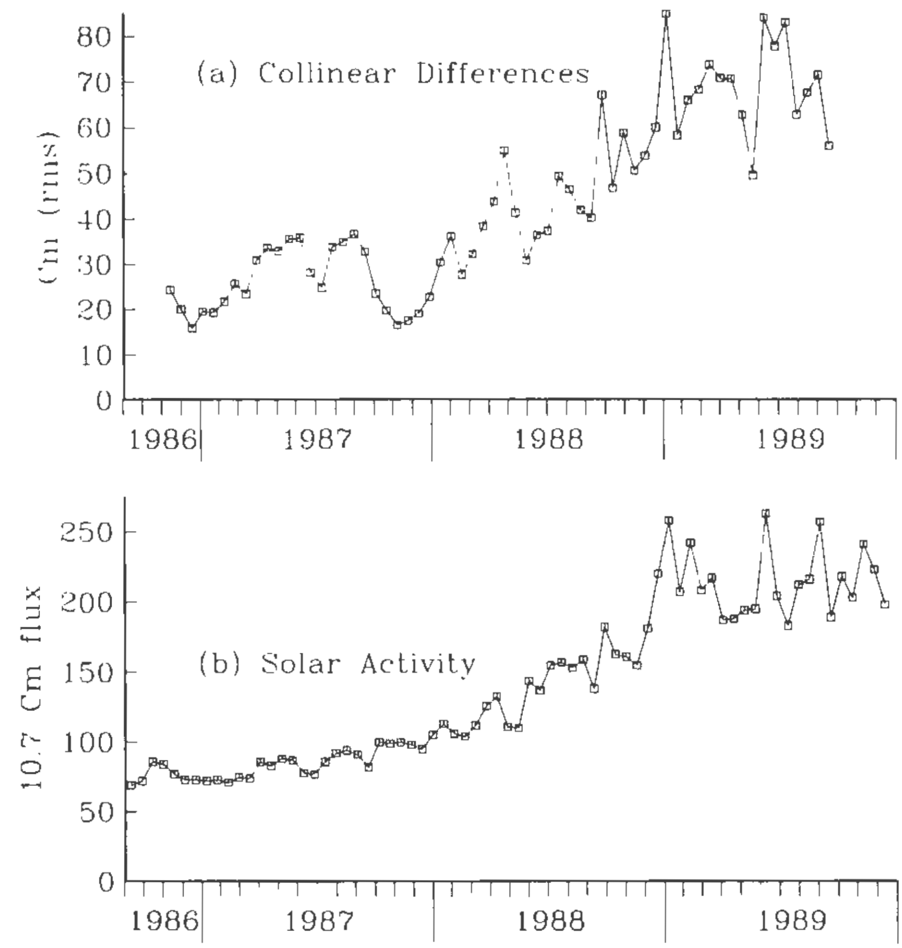


Figure 9. (a) Geosat T2 collinear height differences, averaged globally, for each 17-day cycle relative to cycle 2. Standard corrections were applied, but no adjustment was made for orbit error. Rms differences, when divided by the square root of two, provide a measure of orbit precision. (b) Solar flux averaged over ERM cycles.

(d) Other ERM Orbits

Improvement of the Geosat orbits is an ongoing topic of research, and alternative orbits are available. For example, *Shum et al.* (1990) described a procedure which uses altimeter crossover differences together with the Doppler tracking data for computation of precise Geosat ephemerides. Applying this procedure and using the TEG-2B gravity model *(Tapley et al.* 1991), orbits for the first two years of the ERM have been computed with an averaged radial accuracy of 17 cm rms. Modelling of spacecraft thrusts enabled orbits to be computed for continuous, 17-day arcs. By solving for drag every 12 hours instead of daily and with the use of crossover measurements as additional tracking data, the degradation seen in the T2 orbits during late 1988 due to high drag perturbation has been greatly reduced. The TEG-2B orbits were obtained by simulanteously solving for the altimeter time tag bias, which has typical values of 3-6 ms (see Section XII). *Nerem et al.* (1992b) also report improved Geosat orbits using altimeter heights together with conventional satellite tracking data.

In addition, advances in gravity field models can be expected to further reduce the Geosat orbit error. GEM-T3 (*Lerch et al.* 1992) and TEG-2B are more accurate than GEM-T2, primarily due to the addition of satellite altimeter data from Seasat and Geosat, Spot-2 tracking data, and the inclusion of surface gravity data. While the gravity-induced radial orbit errors for Geosat predicted by the GEM-T2 covariance were 30 cm, T3 predicts radial errors of approximately 12 cm (*Nerem et al.* 1992a).

Another approach has been empirical derivation of global corrections to the T2 orbits using collinear differences. Examples are *Rapp et al.* (1991), *Chelton and Schlax* (1992), and *Wagner and Cheney* (1992), all of whom solved for time-dependent orbit errors using a relatively small number of coefficients for each of the (approximately) 5-day T2 orbital arcs. By removing predominantly the once-per-revolution error, most of the oceanographic signal was retained.

IX. Wet Troposphere

Geosat's primary mission was to map the marine geoid. Since geodetic variations of sea surface topography are typically 1-2 orders of magnitude greater than oceanographic ones, a limited instrument array could satisfy these primary mission goals, and a water vapor radiometer was not included as part of the Geosat payload. The amplitude of the water vapor correction to the altimeter path length ranges from about 35 cm in the tropics to near zero near the poles and can be modeled with an rms accuracy of about 5 cm, entirely adequate for geodetic studies.

Two different water vapor corrections were provided in the NAG GDRs: (1) a climatological value of monthly means based on three years of satellite data from the Nimbus-7 scanning multichannel microwave radiometer, or SMMR, and (2) a value derived from a global model updated at 12-hour intervals at the Fleet Numerical Oceanographic Center (FNOC). Most investigators have used the FNOC corrections since this model could, in principle, provide an accurate representation of the temporal water vapor variations. But the FNOC model lacks much of the detailed horizontal structure of the real troposphere (*Zimbelman and Busalacchi* 1990) and consistently underestimates water vapor in the tropics by as much as 10 cm (*Emery et al.* 1990). Even worse, the FNOC model error varies considerably with time and therefore can interfere with determinations of seasonal and interannual sea level change (*Cheney et al.* 1991). Finally, the basic form of the FNOC model was changed in January 1988 as part of an upgrade to the Navy's operational data assimilation system (*Barker et al.* 1988). This introduced a noticeable discontinuity in the wet troposphere (see *Cheney et al.* 1991b, figure 1).

Two satellites which operated during the Geosat mission have provided significantly more reliable water vapor fields. The principle source of data is the special sensor microwave imager (SSMI) on a U.S. Department of Defense satellite launched in July 1987 (*Wentz* 1989). SSMI data enable derivation of global water vapor fields averaged over 4-day intervals and 1-degree squares with an accuracy of 2 cm. For Geosat data prior to July 9, 1987, water vapor has been retrieved from measurements made by the Tiros operational vertical sounder (TOVS), although averaged over 7-day periods and having an accuracy slightly less than the SSMI (*Emery et al.* 1990).

The TOVS/SSMI wet troposphere values have been incorporated in the T2 GDRs, enabling a much more thorough and quantitative analysis of the effect of water vapor on Geosat sea level. Although the FNOC correction has been retained in the T2 GDRs as one of three wet troposphere values, it is recommended that the TOVS/SSMI value be used, with the SMMR value providing a reasonably accurate auxiliary field.

The TOVS/SSMI correction is not without its own limitations, however. The temporal and spatial smoothing used in the gridding process eliminated some of the fine-scale features of the wet troposphere, although the large-scale, low-frequency information is believed to be quite good. Indeed, *Cheney et al.* (1991b) found significant improvement using TOVS/SSMI for tropical Pacific Geosat analyses where the altimeter data could be averaged over hundreds of kilometers and monthly time periods with little loss of oceanographic information.

At higher latitudes, small-scale/high-frequency water vapor errors undoubtedly remain in the T2 GDRs. To address this problem, *Minster et al.* (1992) used sub-objective mapping to incorporate swaths of SSMI wet troposphere values (rather than the 4-day averages) into the Geosat data. This method retains wavenumber spectral characteristics close to those of the original SSMI data and has resulted in improved Geosat results in the North Atlantic.

Another problem still remaining in the T2 GDRs is an apparent offset of 1.4 cm between the globally averaged TOVS and SSMI fields. This offset was discovered using data from July 1987, in which both TOVS and SSMI water vapor data were independently available. For the same distribution of data along the Geosat track, the following global averages (from 72°N to 63°S) were computed for two ERM cycles:

	Wet Tropo (cm)	
	TOVS	SSMI
Cycle 16	-14.7	-16.1
Cycle 17	-14.7	-16.2

Based on climatology, the TOVS values appear unreasonable. It is therefore recommended that 1.4 cm be subtracted from all TOVS/SSMI wet tropo values prior to July 9, 1987 (the changeover from TOVS to SSMI occurred at the end of the July 8, 1987 GDR). This will make TOVS and SSMI consistent for analyses of global sea level change *(Wagner and Cheney 1992)*, although for regional studies this offset is of no consequence since it would be removed as part of the orbit adjustment.

Finally, it should be pointed out that gaps in coverage by the TOVS and SSMI were treated differently. The swaths of TOVS water vapor data are inherently gappy because the instrument relies on infrared soundings and is therefore subject to cloud interference. Prior to interpolation along the Geosat track, the grids were filled using a 5° x 5° median filter, but some gaps will still be found in the GDRs. One approach to avoid losing altimeter data is to use the climatological SMMR value (item 29 in the GDR) when gaps are encountered.

In contrast, no SSMI gaps will be found in the GDRs except at high latitudes where the radiometer data were contaminated by sea ice. This is partly due to the fact that the SSMI is a microwave instrument, relatively insensitive to clouds. But occasional problems with the spacecraft did create some significant gaps in coverage. The most noteworthy of these was a 40-day loss of data between December 2, 1987 and January 13, 1988 when the satellite experienced problems with thermal control. The approach used by *Wentz (1989)* in producing the along-track Geosat corrections was to create a continuous record by interpolating over all gaps. The Geosat SSMI values for most of December 1987 are therefore interpolations between 4-day average grids separated by about 6 weeks. This is the only gap of this duration, however. All other breaks in the SSMI record are no longer than a few days.

X. Ionosphere

Geosat had a single-frequency altimeter requiring use of a model (*Klobuchar* 1987), driven by daily values of solar flux, to estimate the path length correction due to the ionosphere. As shown in Figure 10, Geosat was launched during a time of solar minimum, but during 1988 and 1989 the flux increased dramatically. Although the model was valid only for solar flux values from 75 to 230, ionosphere corrections were generated for days outside of this range by setting the input to the limiting value. For example, if the actual flux for a given day was 68, the model was run using a flux of 75 instead. Days for which the actual flux was outside of the model limits were indicated by setting flat bit 13 = 1.

It should be noted, however, that the Geosat model only attempts to reproduce the large-scale features of the ionosphere, as seen in the profile in Figure 7. Furthermore, it has been estimated that the model values are only accurate at the 50% level (*Musman* 1990). But much of the residual error is removed together with the orbit error when collinear or crossover adjustments are performed during typical analysis procedures. For regional sea level variability studies, ionosphere error is therefore probably not a limiting factor.

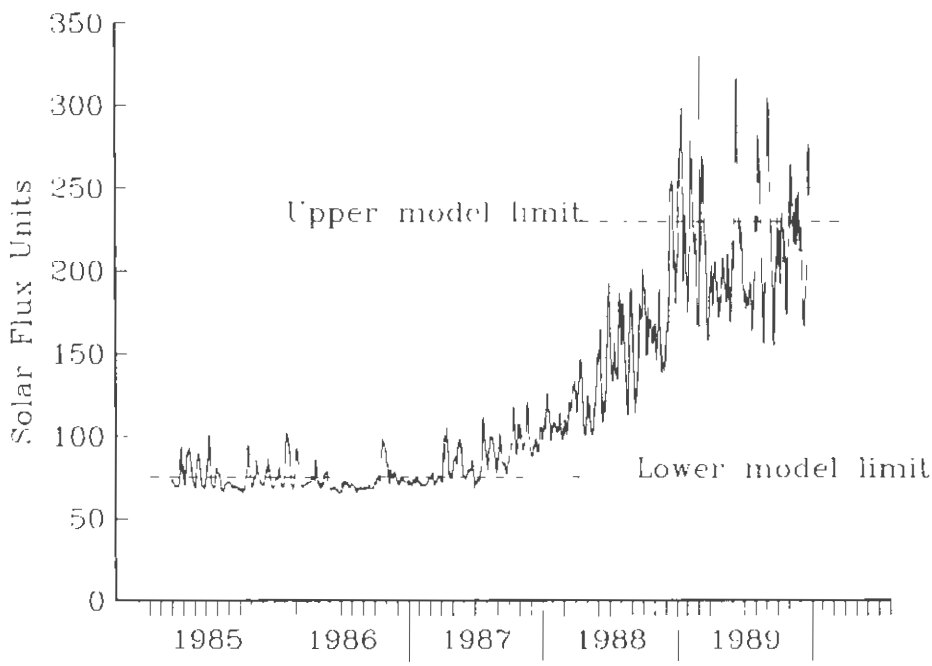


Figure 10. Daily values of solar flux during the Geosat mission. Flux has unit of 10^{-22} watts per m^2 per Hz. The Geosat model was only valid for fluxes of 75 - 230, but ionosphere corrections were computed for days outside this range by setting the input to the limiting value.

The situation is different for studies of the change of global average sea level (*Wagner and Cheney* 1992). Because of the 11-year period of the solar cycle, the ionospheric correction is obviously critical, yet little is known of its long-term accuracy. Of all the media corrections, the ionosphere is not subject to conservation rules which impose practical absolute limits over the long term. Thus there are natural limits to the water vapor, wave activity, and tropospheric pressure changes which tend to keep interannual and secular effects within fairly narrow bounds. But even at the peak of the solar cycle the ionosphere is usually far from saturated. Shown in Figure 11 is the Geosat ionosphere correction averaged globally over each 17-day repeat cycle during the first 2.5 years of the ERM. Values rise from 2 cm at the beginning of this record to 6 cm in 1989. The important question is: how reliable is the Geosat ionosphere model for global averages?

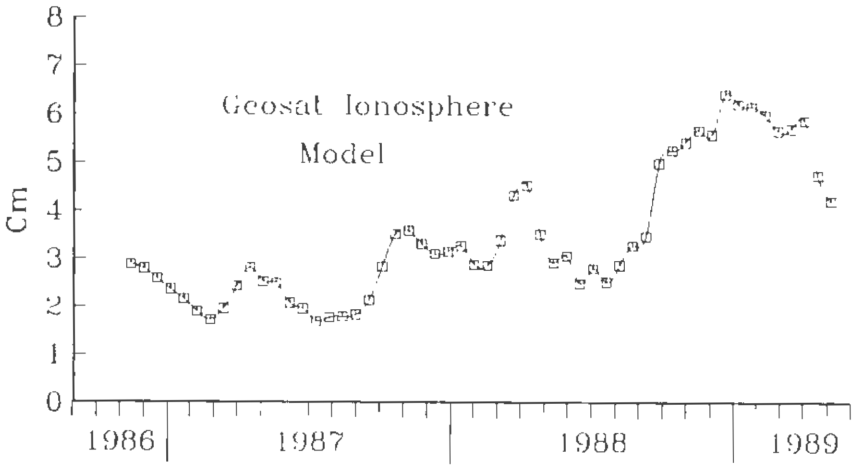


Figure 11. Ionosphere correction from the T2 GDRs. Along-track values were averaged globally for each 17-day cycle during the first 2.5 years of the ERM (from Wagner and Cheney 1992).

Figure 12 compares the performance of the Geosat model with Faraday rotation measurements made in Puerto Rico based on signals from geostationary satellites for two given months. In November 1986, when the solar flux was relatively low, the Geosat model overestimated the ionosphere correction by 0.8 cm but otherwise the model is fairly reasonable. However, in July 1989, when the flux was a factor of two higher, the Geosat model underestimated the ionosphere by an average of 2.7 cm and does not reflect the large range of variations seen in the Faraday measurements.

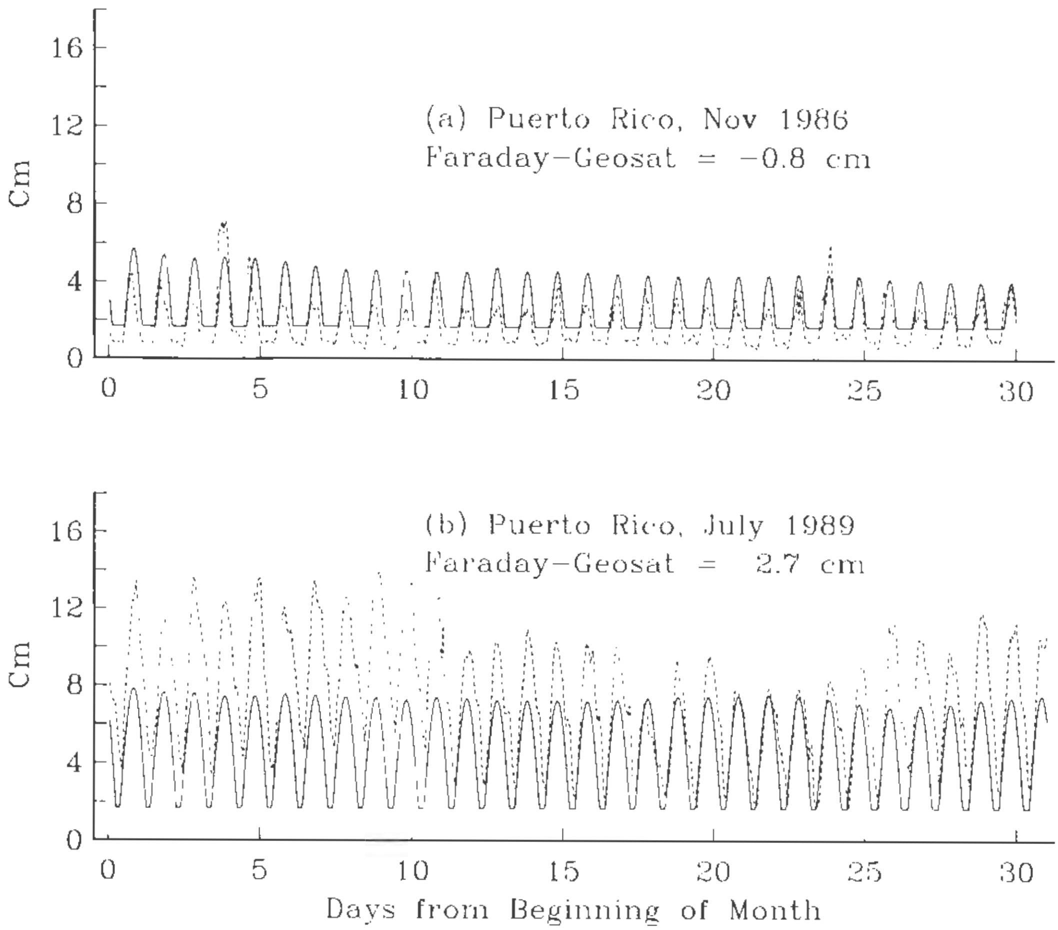


Figure 12. Ionospheric delay at Ramey, Puerto Rico: Geosat model (solid) vs. Faraday rotation measurements (dashed). (a) November 1986. Solar flux in this period is near its minimum for the ERM, 71-91 solar flux units at 10.7 cm. Model values were 0.8 cm too high. (b) July 1989. Solar flux in this period is relatively high, 176-195 solar flux units. Model values were 2.7 cm too low. Note the insensitivity of the model to solar variations. From Wagner and Cheney (1992).

Although the large daytime values of the ionospheric correction are normally considered to be most important, the crude treatment of the nighttime ionosphere by the model is also seen to be a major problem. The model assumes a constant minimum night activity regardless of solar conditions. Figure 12a shows that at low sun, the actual nighttime level is significantly smaller than the model cutoff. Figure 12b, on the other hand, shows that with an active sun the nighttime levels tend to be much higher than the same model cutoff, and also much more variable than at low sun levels. We conclude that while the Geosat model may be a fair predictor of average solar conditions, it seems to overestimate the ionosphere during periods of low solar activity and seriously underestimate it during high solar times.

The results at Puerto Rico are similar to those at other Faraday rotation sites (Hawaii, Japan, Taiwan), but only mid-latitude, northern hemisphere locations are available for such comparisons during the ERM. In order to determine whether these point measurements are representative of the Geosat model performance for the global ionosphere, we can take advantage of results derived by *Escudier et al. (1991)* using the two-frequency DORIS Doppler system on the SPOT-2 satellite launched in 1990. The DORIS data permit a direct measure of ionospheric activity worldwide because the transmitting ground stations provide almost continuous coverage of the SPOT satellite in its near-polar orbit. Figure 13 shows Geosat altimeter delay values for the globally-averaged ionosphere determined by DORIS at 3-day intervals during October 1990. Also in this figure are corresponding values generated by the Geosat model along the same SPOT ground track and using daily values of solar flux as input (the values ranged from 153 to 222 during the month). We again see that the Geosat model values are far too low during periods of high solar flux, in this case by an average 4.2 cm for October 1990. We conclude that as solar maximum approached, the Geosat model severely underestimated the global ionosphere, although the exact magnitude of the error is uncertain.

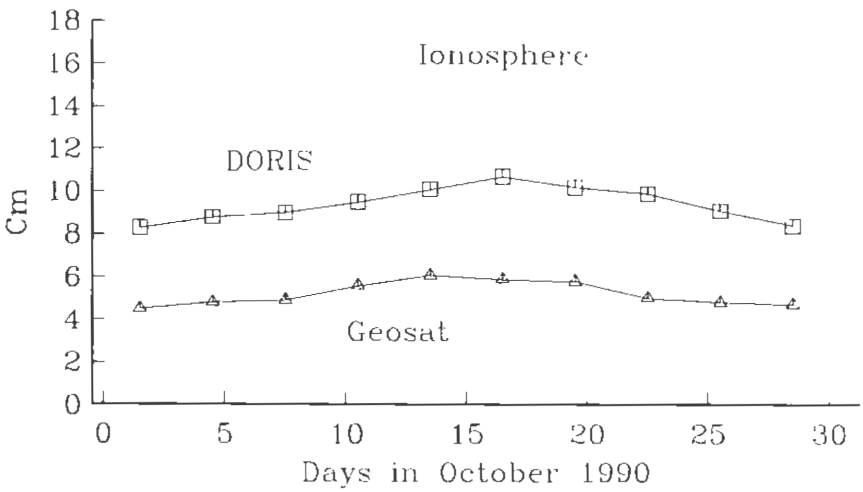


Figure 13. Global ionospheric delay averaged along the SPOT-2 ground track at 3-day intervals during October 1990, (a) measured by the DORIS dual-frequency system and (b) estimated from the Geosat model. As found in the Faraday rotation comparison, the Geosat model underestimates the ionosphere during times of large solar flux (here, 153-222 solar flux units). From Wagner and Cheney (1992).

XI. Spacecraft Attitude

Geosat maintained nadir pointing for the altimeter antenna by means of a gravity gradient stabilization system. This method gave outstanding mechanical reliability, but allowed excursions off-nadir of 1 degree or more. Because the beam width of the altimeter was only 2 degrees, the nadir footprint was not fully illuminated when attitude was greater than about 1 degree. As discussed by *Kilgus (1987)*, large attitude excursions adversely affected altimeter performance in the following way. Before the altimeter could "lock-on" to the return radar pulse, an acquisition mode with a wide range window was used to determine the approximate distance to the surface. This measurement was then used to narrow the window and allow precise range tracking. Because the acquisition process was sensitive to signal distortion accompanying high attitude angles, transitions from land to water for off-nadir angles greater than about 1.1 degrees caused irrecoverable data loss until attitude decreased to less than 1.1 degrees when precise tracking resumed.

The underlying cause of Geosat's attitude problem appeared to be solar radiation pressure (with smaller contributions from magnetic imbalances, atmosphere, gravity, etc.). *Holdridge (1988)* found that simulations involving solar radiation torques provided attitude disturbances with periods and spatial patterns that resembled the data gaps. Solar radiation torque applied at the orbital period combined with the pitch libration period of the spacecraft to produce a maximum pitch disturbance approximately every 5 hours. The Earth completes about one-fifth of a rotation in this time, creating five evenly spaced orbital bands of maximum attitude in each hemisphere.

In addition, the 11-month cycle of the angle between the Geosat ascending node and solar ascending node produced variations in data gaps with a comparable period. This is reflected in the series of ground track maps in the appendix. For example, excellent coverage was obtained in the Southern Hemisphere at the beginning of the ERM, and again near the end of the first year, but significant data loss occurred during the middle of the year.

Although progressively larger amounts of data were lost with the approach of solar maximum, analyses have indicated that as long as the altimeter was in its precise tracking mode, attitude had no effect on quality of the sea height measurements. In contrast, sigma naught and significant wave height may be less reliable at large values of attitude since these measurements are more sensitive to attitude. Unfortunately, it is difficult to determine the effect of attitude of these parameters because, unlike the permanent geoid topography, their true values vary with time. It is recommended that Geosat wind and wave data be used with caution when attitude is greater than approximately 1.1 degrees.

It is interesting to note that spacecraft maneuvers during the ERM, performed to maintain the collinear ground track, did not have any significant adverse impact on attitude. Only a very small thrust was required to compensate for atmospheric drag on Geosat.

XII. Time Tag Errors

Accurate time tags are fundamental to altimetry because of the rapid rate of change of the satellite height relative to the sea surface. The Earth's oblate shape combined with a slightly eccentric orbit can produce relative height rates as large as 20 m/s. A constant timing error of 1 ms can therefore create height uncertainties as large as 2 cm. But such a timing bias can be determined from altimetry itself because of its characteristic twice-per-revolution signature in the data. *Marsh and Williamson (1982)* and *Schutz et al. (1982)* were thus able to verify the large, 79 ms timing bias initially contained in the Seasat altimeter data.

Initial analyses of Geosat ERM data showed conclusively that the timing bias was small, and a value of zero was recommended in the GDR handbook. A value of 5 ± 3 ms was later determined by *Shum et al. (1990)*. More exhaustive analyses have now converged on a value of approximately 3.5 ms, averaged over the ERM (*C. Wagner and C.-K. Shum, personal communication*).

In addition, evidence based on SDR header time tags and their correlated frame counts suggests that the timing bias changed slightly during the ERM, as summarized in figure 14. The Geosat interface control document (*JHU/APL 1985*, p. 75) provides a formula for computing the minor frame count span, i.e. the *10/s* altimeter data rate, for each day of data. At the beginning of the ERM this span was 0.0979921662 s. Given no clock drift, the spacing between consecutive *1/s* GDR values should therefore be either 979.921 or 979.922 ms (10 minor frames). However, by the end of the ERM this span had increased by almost 2 ms. Figure 14 shows the accumulated daily deviations from the initial GDR record spacing,

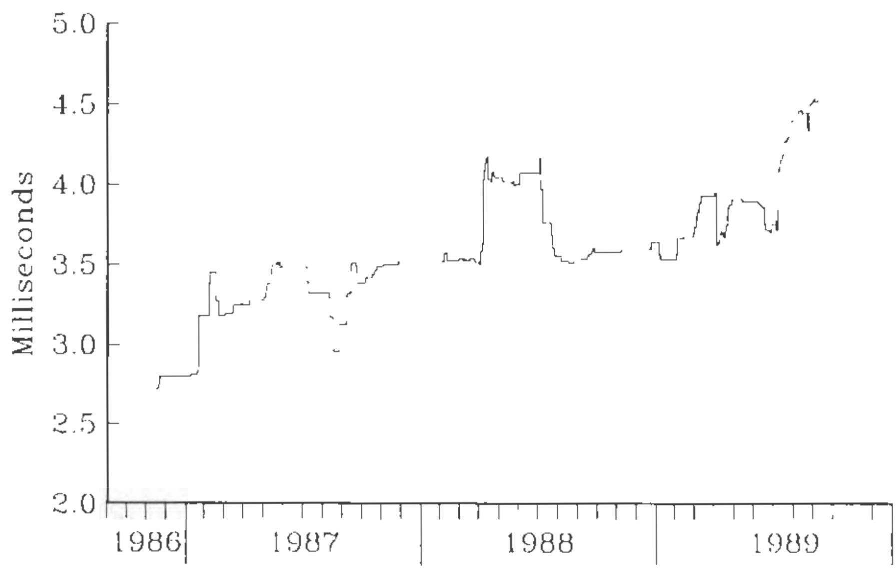


Figure 14. Accumulated deviations of the GDR time tag spacing from its initial value. We interpret this as drift in the altimeter timing bias with respect to its mean value of 3.5 ms. Although a trend of about 0.5 ms per year is evident, errors of this magnitude are negligible for most applications.

relative to the absolute timing bias of 3.5 ms (estimated independently). We have no explanation for the occasional jumps in the GDR time interval, but the data suggest a drift of perhaps 0.5 ms per year. Investigators wishing to apply this timing correction to their data should subtract the value from the time given in the T2 GDRs. Because of the relatively small amplitude of this correction, and its dominant frequency of twice-per-revolution, the Geosat timing bias will probably be significant only for global-scale studies. In applications where short-arc adjustments are used to eliminate orbit error, most of the timing error is also removed. (Note that similar studies of time tag errors have not been performed for the GM GDRs.)

Timing errors of a different nature, and of much large magnitude, were discovered in a total of ten days of the NAG GDRs. For unknown reasons, incorrect times were contained in several consecutive days of SDR headers. These errors were corrected in the T2 GDRs by recovering the necessary SDR tapes from the JHU APL archive and interpolating across the bad timing values. The following is a list of T2 GDRs which were reprocessed and the approximate magnitude of the original error.

	Timing Error
1988 Days 90-93	+ 20 ms
1988 Days 115-116	+ 20 ms
1989 Days 4-7	- 150 ms

XIII. Altimeter Calibrations

Time tag errors discussed in the previous section are manifested as twice-per-revolution signatures in altimeter height and are therefore somewhat like an orbit error of known frequency. But such errors do not directly affect determination of the change of global sea level. Two factors that do have implications in this area have been discussed by *Wagner and Cheney (1992)* and are included in this section.

(a) Altimeter drift. Unlike Seasat, Geosat did not carry a laser reflector for absolute calibration of the altimeter. However, drift of the altimeter height was monitored onboard by processing a sample of the transmitted pulse through the system and tracking it as a point target *(MacArthur et al. 1987)*. The result of this internal calibration (Figure 15a) is problematic because it appears to be much more sensitive to temperature effects than the altimeter itself. For example, the anomalies in the calibrator near the beginning of each year occur when the spacecraft orbit is in the earth's shadow. If we neglect these time periods, there appears to be a slow downward trend in the calibration which may represent a steady degradation of circuitry in the altimeter (the sign of this drift would cause an apparent decline of global sea level). We conclude that a correction of approximately 0.2 cm per year should be applied to the Geosat data for investigations of global sea level (the solid line in Figure 15a).

(b) Clock drift. Onboard calibration was also performed for the spacecraft clock which timed the radar pulses. A nearly constant drift of about 3 parts per billion per year was found *(John MacArthur, personal communication, 1991)*, equivalent to about 0.2 cm per year. In October 1987 a single step correction of 10 parts per billion was made to the Geosat clock to compensate for this drift. The net effect on altimeter height of the uncompensated part of the drift together with the one-time correction is shown in Figure 15b. Over the first 2.5 years of the ERM the average error is approximately 0.2 cm per year.

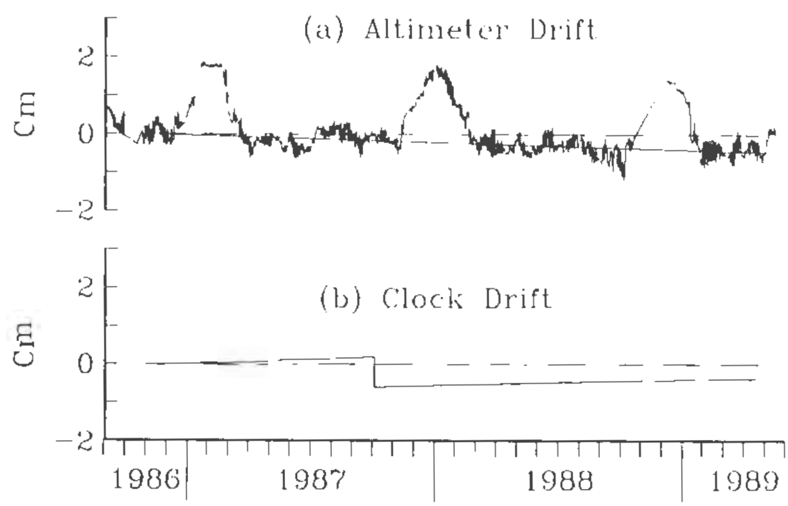


Figure 15. Geosat onboard calibrations of (a) altimeter drift and (b) clock drift. In each case the magnitude is approximately 0.2 cm per year. This correction is only important for calculation of global sea level change. From Wagner and Cheney (1992).

References

Barker, E.H., J.S. Goerss, and N.L. Baker, 1988: The Navy's operational multivariate optimum interpolation analysis method, *Proceedings, AMS Conference on Numerical Weather Prediction,* Baltimore, MD.

Born, G.H., F.G. Lemoine, and M.J. Crawford, 1988: Geosat ERM--Orbit determination, *Adv. Astronautical Sci., 65,* 65-81.

Cartwright, D. E., and A. C. Edden, 1973: Corrected tables of tidal harmonics, *Geophys. J. of the Roy. Soc., 23,* 253-264.

Cartwright, D. E., and R. J. Tayler, 1971: New computations of the tide generating potential, *Geophys. J. of the Roy. Soc., 23,* 45-74.

Chelton, D.B. and M.G. Schlax, 1992: Spectral characteristics of time-dependent orbit errors in altimeter height measurements, *J. Geophys. Res.,* in press.

Cheney, R.E., B.C. Douglas, and R.W. Agreen, 1991a: Geosat altimeter crossover difference handbook, *NOAA Manual NOS NGS 6,* Rockville, MD, 32 pp.

Cheney, R.E., W.J. Emery, B.J. Haines, and F. Wentz, 1991b: Recent improvements in Geosat altimeter data, *EOS, 72* (51), 577-580.

Cheney, R.E., B.C. Douglas, R.W. Agreen, L. Miller, and N.S. Doyle, 1988: The NOAA Geosat geophysical data records: Summary of the first year of the exact repeat mission, *NOAA Tech. Memo. NOS NGS 48,* Rockville, MD, 20 pp.

Cheney, R.E., B.C. Douglas, R.W. Agreen, L. Miller, D.L. Porter, and N.S. Doyle, 1987: Geosat altimeter geophysical data record user handbook, *NOAA Tech. Memo. NOS NGS 46,* Rockville, MD, 32 pp.

Cheney, R.E., B.C. Douglas, R.W. Agreen, L. Miller, D. Milbert, and D. Porter, 1986: The Geosat altimeter mission: A milestone in satellite oceanography, *EOS, 67,* 1354-1355.

Dobson, E.B., Wilkerson, J., Agreen, R., and Douglas, B., 1988: GEOSAT altimeter wind and wave data record user handbook, *Johns Hopkins University Applied Physics Laboratory Tech. Report S1R88U-009,* Laurel, MD, 28 pp.

Douglas, B.C. and R.E. Cheney, 1990: Geosat: Beginning a new era in satellite oceanography, *J. Geophys. Res., 95* (C3), 2833-2836.

Doyle, N.S., Cheney, R.E., B.C. Douglas, R.W. Agreen, L. Miller, and E.L. Timmerman, 1989: The NOAA Geosat geophysical data records: Summary of the second year of the exact repeat mission, *NOAA Tech. Memo. NOS NGS 49,* Rockville, MD, 20 pp.

Doyle, N.S., Cheney, R.E., B.C. Douglas, R.W. Agreen, L. Miller, and E.L. Timmerman, 1990: The NOAA Geosat geophysical data records: Summary of the third year of the exact repeat mission, *NOAA Tech. Memo. NOS NGS 51,* Rockville, MD, 19 pp.

Emery, W.J., G.H. Born, D.C. Baldwin, and C.L. Norris, 1990: Satellite-derived water vapor corrections for Geosat altimetry, *J. Geophys. Res., 95* (C3), 2953-2964.

Escudier, P., N. Picot and O.Z. Zanife, 1991: Altimetric ionospheric correction using doris Doppler data, CNES-Research and Application Group in the Earth Sciences and the Environment Report, Toulouse, France.

Haines, B.J., G.H. Born, R.G. Williamson, and C.J. Koblinsky, 1992: Application of the GEM T2 gravity model to altimetric satellite orbit computation, *J. Geophys. Res.*, in press.

Haines, B.J., G.H. Born, G.W. Rosborough, J.G. Marsh, and R.G. Williamson, 1990: Precise orbit computation for the Geosat exact repeat mission, *J. Geophys. Res., 95* (C3), 2871-2886.

Holdridge, M. E., 1988: Results from Geosat ERM data gap/attitude analysis, JHU APL memo. Laurel, MD.

Kilgus, C. C., 1987: GEOSAT coverage of the ocean, JHU APL memo., Laurel, MD.

Klobuchar, J.A., 1987: Ionospheric time-delay algorithm for single-frequency GPS users, *IEEE Trans., Aerosp. Electron Syst., AES-23,* 325-331.

JHU APL, 1985: GEOSAT-A Data Users/Ground System Interface Control Document (ICD), *JHU APL, 7292-9510 Rev. 1,* Laurel, MD, 122 pp.

JHU APL, 1981: The U.S. Navy Navigation Satellite System, *JHU APL Technical Digest, 2* (1).

Jones, S.C., B.E. Tossman, and L.M. Dubois, 1987: The Geosat ground station, *JHU APL Technical Digest, 8* (2), 190-196.

Lerch, F. J., et al., 1992: Geopotential models of the Earth from satellite tracking, altimeter, and surface gravity observations: GEM-T3 and GEM-T3S, *NASA Tech. Memo. 104555,* Greenbelt, MD.

Lerch, F. J., S. M. Klosko, R. E. Laubscher, and C. A. Wagner, 1979: Gravity model improvement using GEOS-3 (GEM 9 and 10), *J. Geophys. Res., 84* (B8), 3897-3916.

MacArthur, J.L., Marsh, P.C., and J.G. Wall, 1987: The Geosat radar altimeter, *JHU APL Technical Digest, 8* (2), 176-181.

Marks, K.M., D.C. McAdoo, and D.T. Sandwell, 1991: Geosat GM data reveal new details of ocean floor, *EOS, 72,* 145-149.

Marsh, J.G., et al., 1990: The GEM-T2 gravitational model, *J. Geophys. Res., 95* (C8), 13129-13150.

Marsh, J.G. and R.G. Williamson, 1982: Seasat altimeter timing bias estimation, *J. Geophys. Res., 87* (C5), 3232-3238.

Miller, L. and R.E. Cheney, 1990: Large-scale meridional transport in the tropical Pacific Ocean during the 1986-87 El Nino, *J. Geophys. Res., 95* (C3), 17905-17920.

Minster J-F., D. Jourdan, E. Normant, C. Brossier, and M.C. Gennero, 1992: An improved SSMI water vapor correction for Geosat altimeter data, *J. Geophys. Res.*, in press.

Musman, S., A. Drew, and B. C. Douglas, 1990: Ionospheric effects on Geosat altimeter observations, *J. Geophys. Res. 95 (C3)*, 2965-2967.

Nerem, R. S., F. J. Lerch, C. J. Koblinsky, S. M. Klosko, G. B. Patel, and R. G. Williamson, 1992a: Determining large scale dynamic topography from satellite altimetry in GEM-T3, *J. Geophys. Res.,* in press.

Nerem, R. S., C. J. Koblinsky, S. M. Klosko, and R. G. Williamson, 1992b: Observing large scale sea surface topography from space: Part I- techniques and initial results, *J. Geophys. Res.,* in press.

Pope, A.J., 1976: The statistics of residuals and the detection of outliers, *NOAA Tech. Rep. NOS 65 NGS 1,* Rockville, MD, 133 pp.

Prabhakara, C., D. A. Short, and B. E. Vollmer, 1985: El Nino and atmospheric water vapor: observations from Nimbus 7 SMMR, *J. Clim. Appl. Met., 24,* 1311-1324.

Rapp, R. H., Y.M. Wang, and N.K. Pavlis, 1991: The Ohio State 1991 geootential and sea surface topography harmonic coefficient models, *Dept. Geodetic Science and Surveying, Report No. 410,* Ohio State University, Columbus, OH.

Rapp, R.H. and N.K. Pavlis, 1990: The development and analysis of geopotential coefficient models to spherical harmonic degree 360, *J. Geophys. Res., 95* (B3), 21889-21911.

Rapp, R. H., 1978: A global 1 x 1 anomaly field combining satellite, GEOS-3 Altimeter and Terrestrial Anomaly Data, *Dept. Geodetic Science and Surveying, Report No. 278,* The Ohio State University, Department of Geodetic Science and Surveying, Columbus, OH.

Schutz, B.E., B.D. Tapley, and C.-K. Shum, 1982: Evaluation of the Seasat altimeter time tag bias, *J. Geophys. Res., 87* (C5), 3239-3246.

Schwiderski, E. W., 1980: On charting global tides, *Rev. of Geophys. Space Phys., 18* (1), 243-268.

Schwiderski, E.W. and Szeto, L. T., 1981: The NSWC global ocean tide data tape, its features and application, random-point program, *NSWC Technical Report 81-254,* Naval Surface Weapons Center, Dahlgren, VA.

Shum, C., D. Yuan, J. Ries, J. Smith, B. Schutz, and B. Tapley, 1990: Precision orbit determination for the Geosat exact repeat mission, *J. Geophys. Res., 95* (C3), 2887-2898.

Shum, C., B. Schutz, J. Ries, and B. Tapley, 1987: Digitized global land-sea map and access software, *Bull. Geod., 61,* 311-317.

Tapley, B., C. Shum, D. Yuan, J. Ries, R. Eanes, M. Watkins and B. Schutz, 1991: University of Texas Earth Gravity Field Model, *Proc. IUGG Symposium*, Vienna, Austria.

Tapley, B. D., J. B. Lundberg, and G. H. Born, 1982: The Seasat altimeter wet tropospheric range correction, *J. Geophys. Res., 87* (C5), 3213-3220.

VanDam, T.M., 1991: Atmospheric loading response of the solid earth and oceans, Ph.D. thesis, Dept. of Geophysics, Univ. Colo., Boulder, CO.

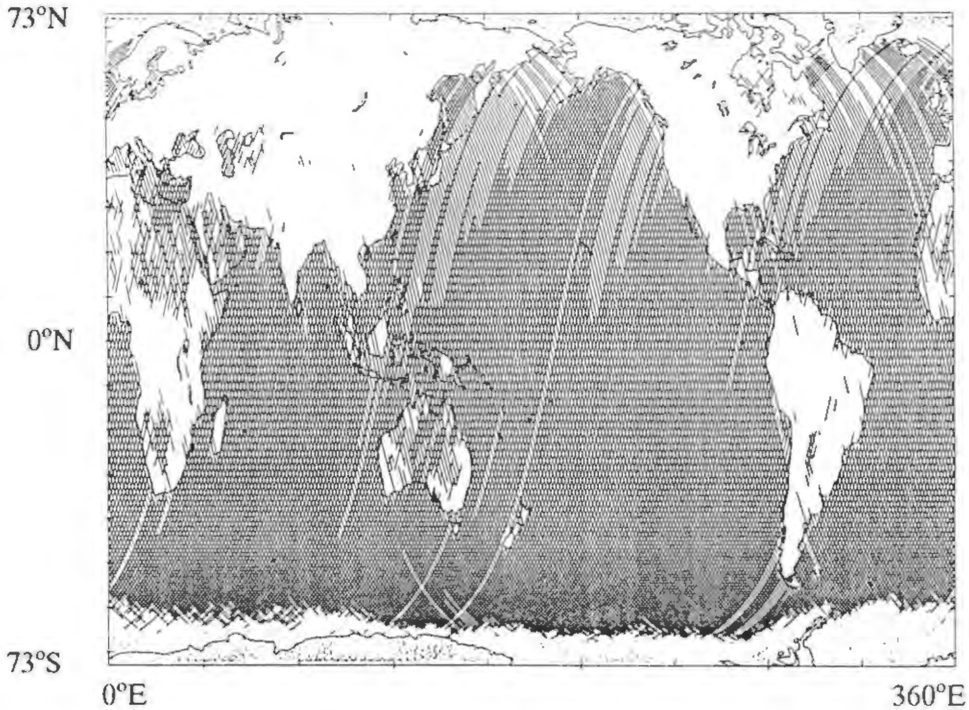
Wagner, C.A. and R.E. Cheney, 1992: Global sea level change from satellite altimetry, *J. Geophys. Res.*, in press.

Wentz, F., 1989: User's manual for the collocated Geosat SSM/I tape, Remote Sensing Systems, Santa Rosa, CA.

West, G.B., 1986: Data processing system specifications for the Geosat satellite radar altimeter, *NSWC TR 86-149*, Naval Surface Weapons Center, Dahlgren, VA.

Zimbelman, D.F., and A.J. Busalacchi, 1990: The wet tropospheric range correction: product intercomparisons and the simulated effect for tropical Pacific altimeter retrievals, *J. Geophys. Res., 95* (C3), 2899-2922.

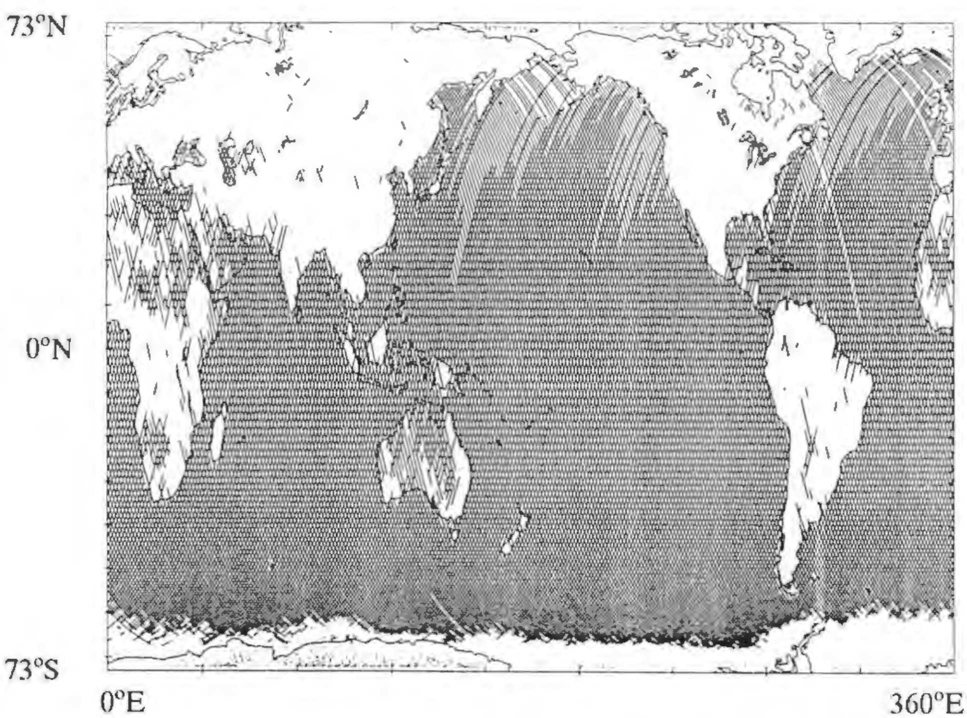
Appendix



ERM Cycle 1

Days 312-328

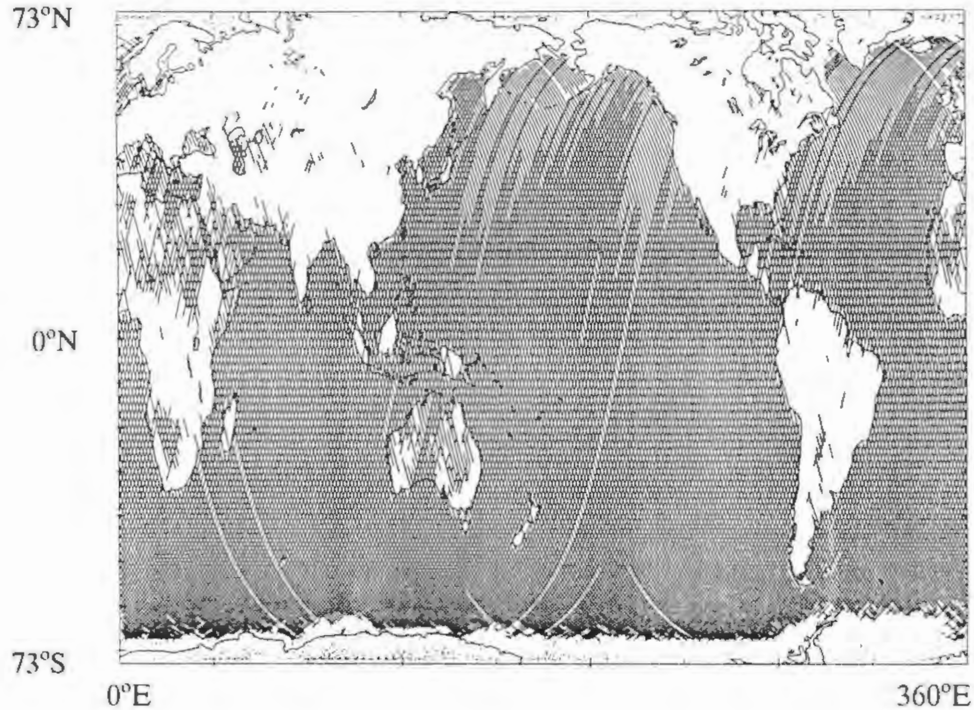
1986



ERM Cycle 2

Days 329-345

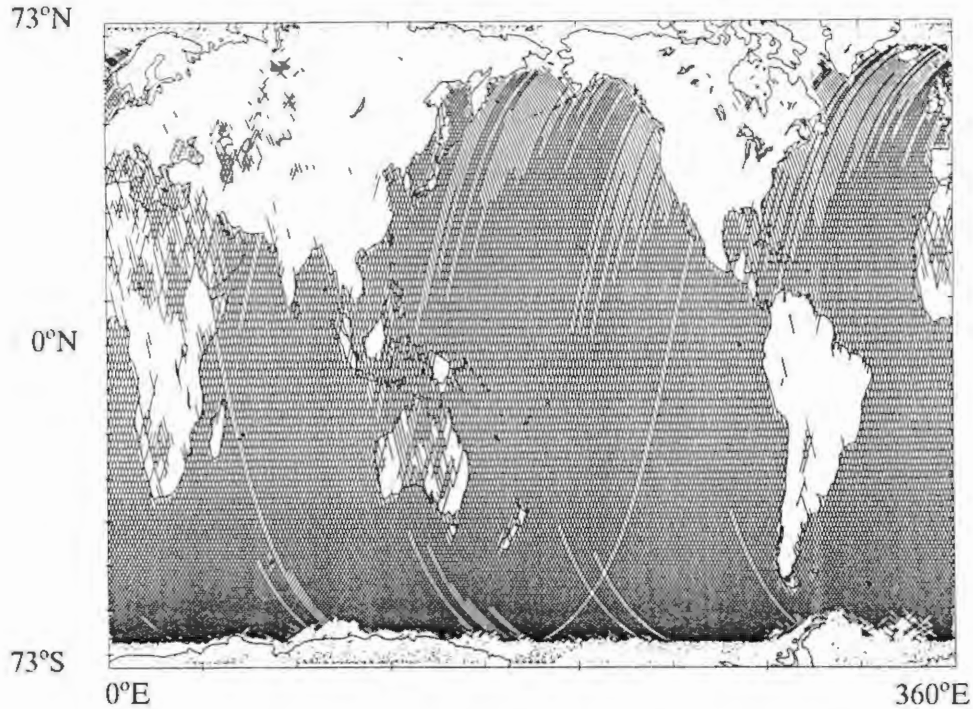
1986



ERM Cycle 3

Days 346-362

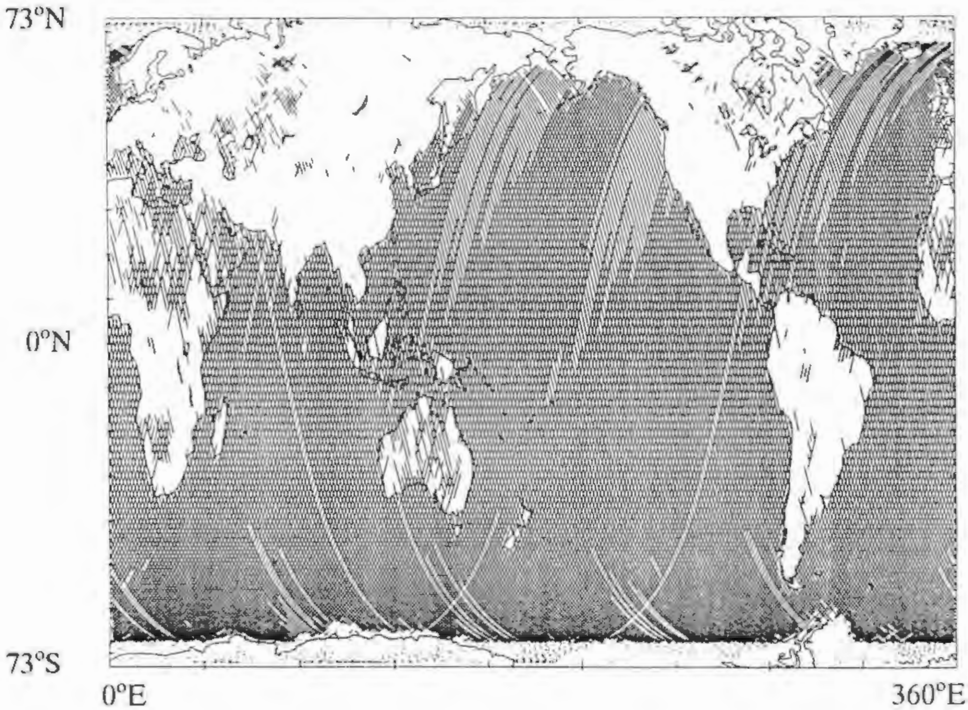
1986



ERM Cycle 4

Days 363-014

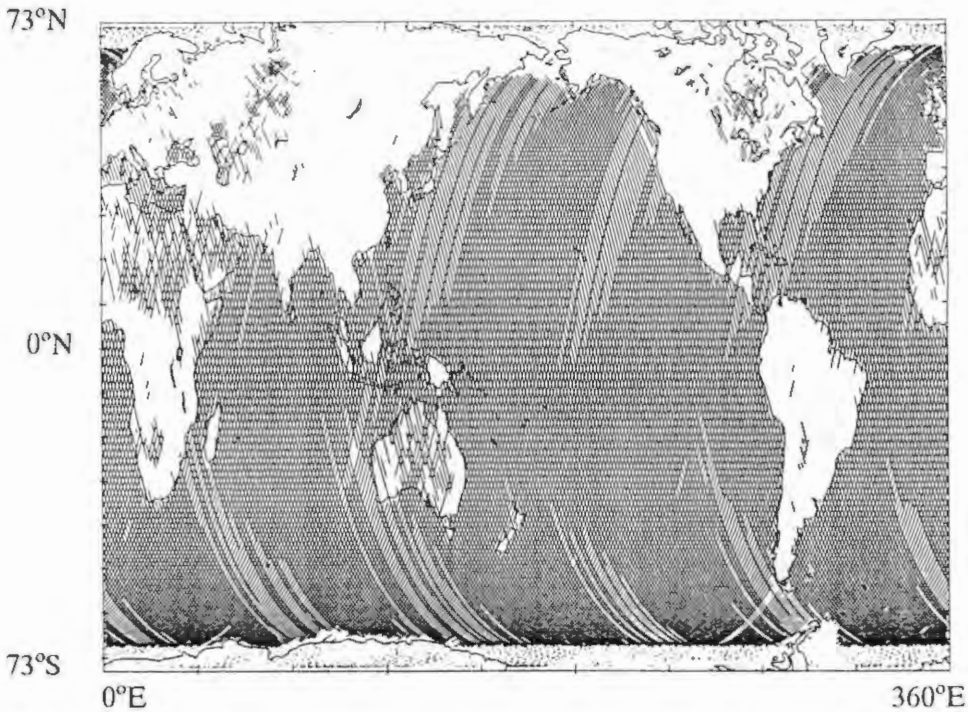
1986-87



ERM Cycle 5

Days 015-031

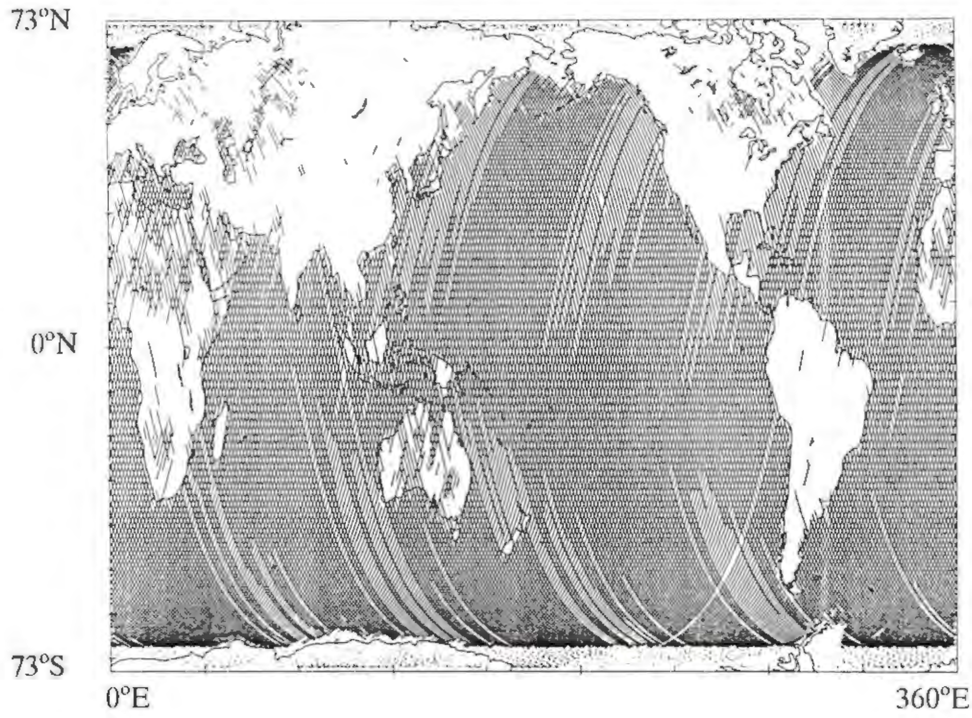
1987



ERM Cycle 6

Days 032-048

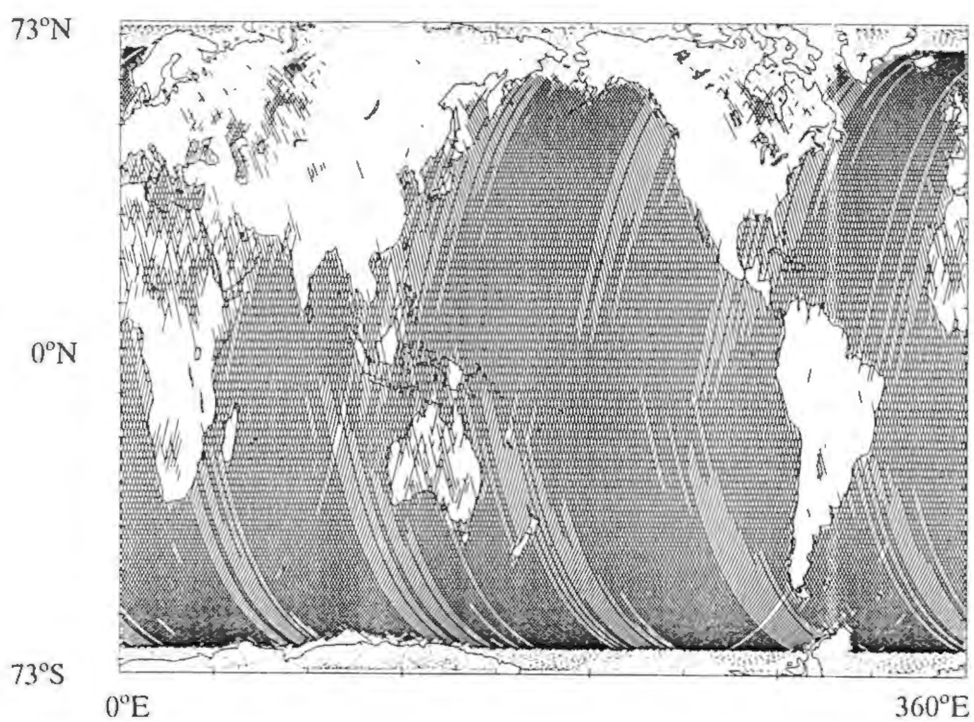
1987



ERM Cycle 7

Days 049-065

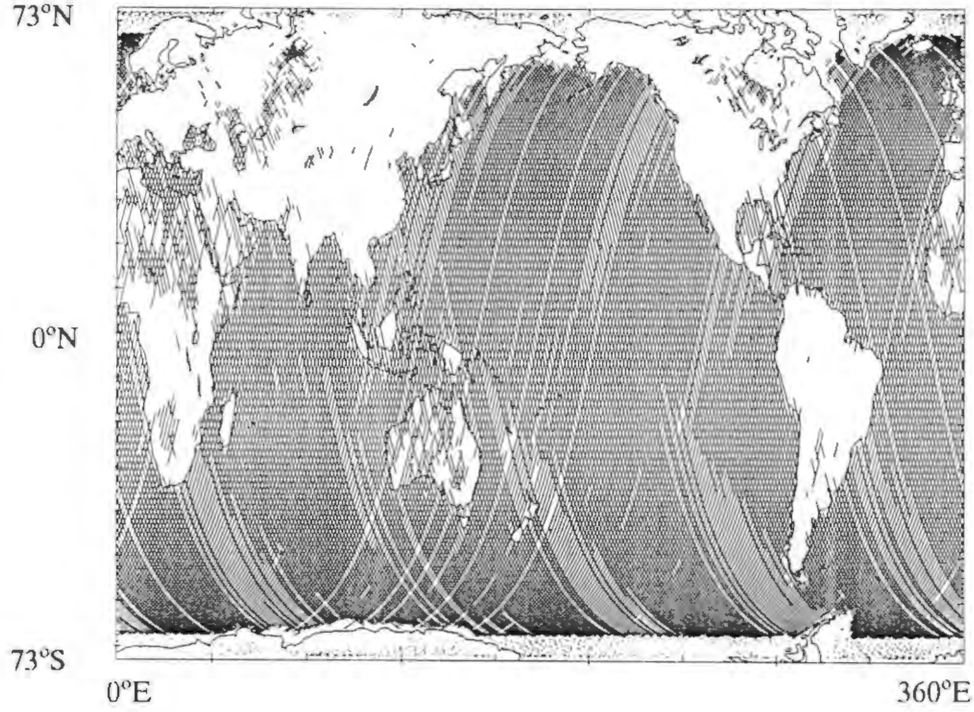
1987



ERM Cycle 8

Days 066-082

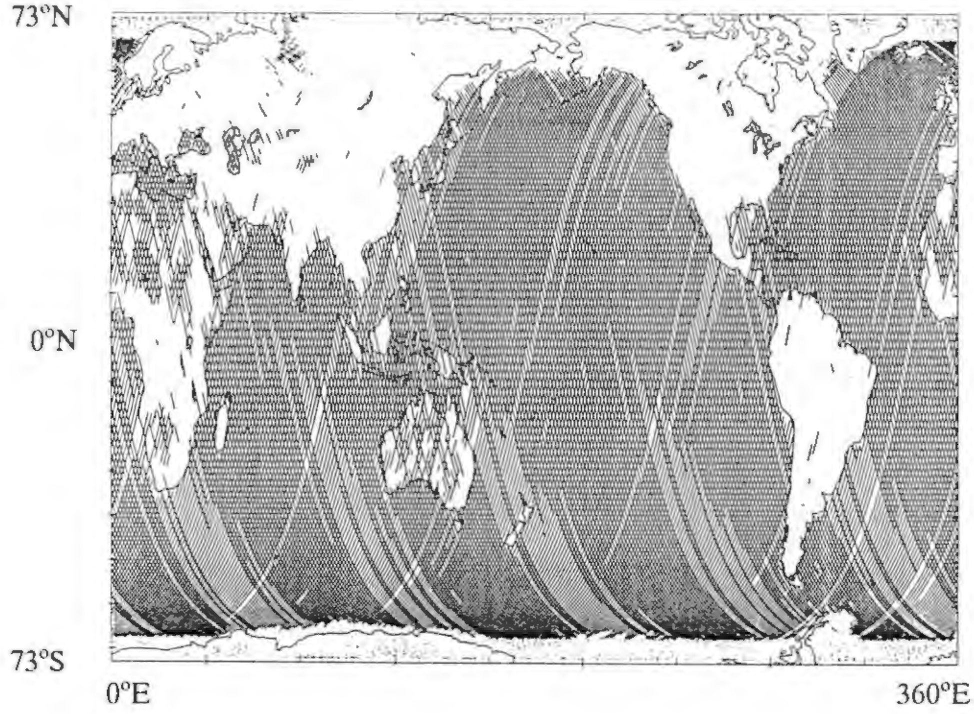
1987



ERM Cycle 9

Days 083-099

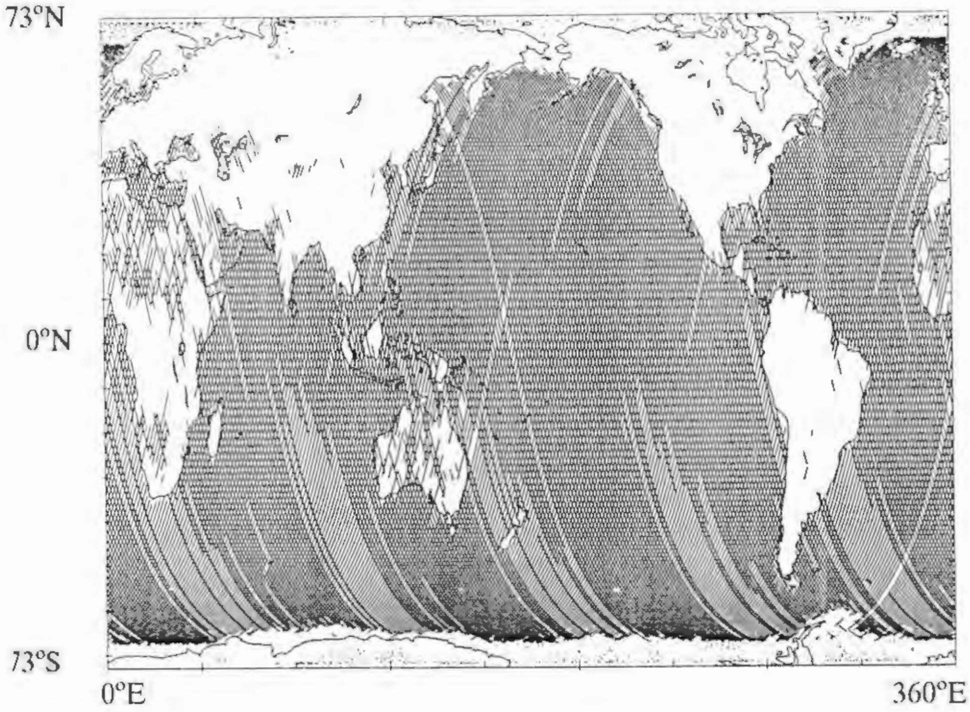
1987



ERM Cycle 10

Days 100-116

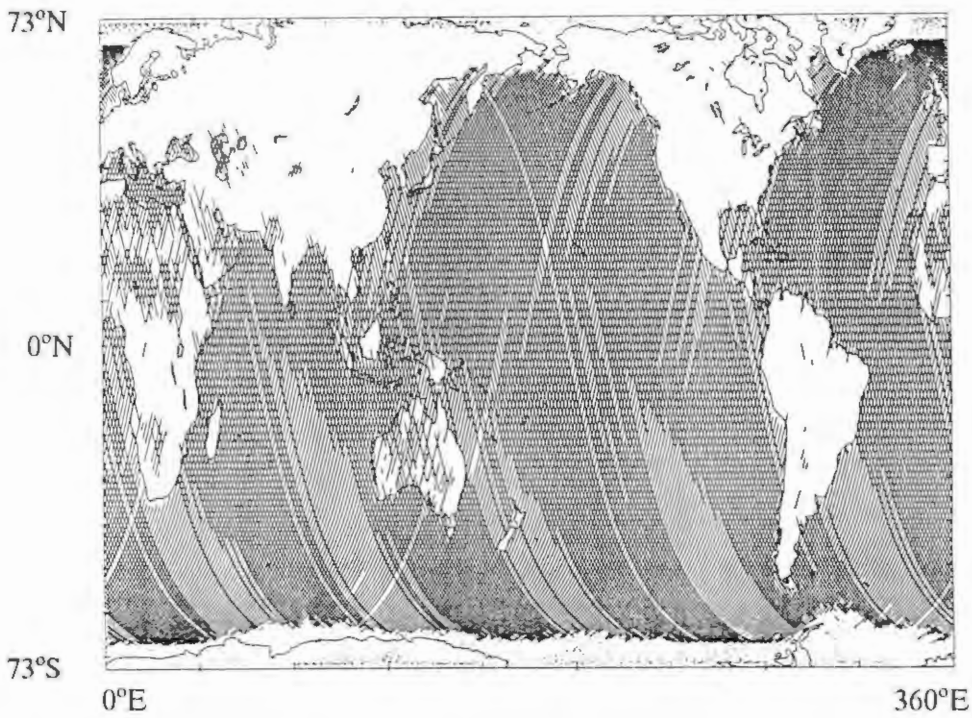
1987



ERM Cycle 11

Days 117-133

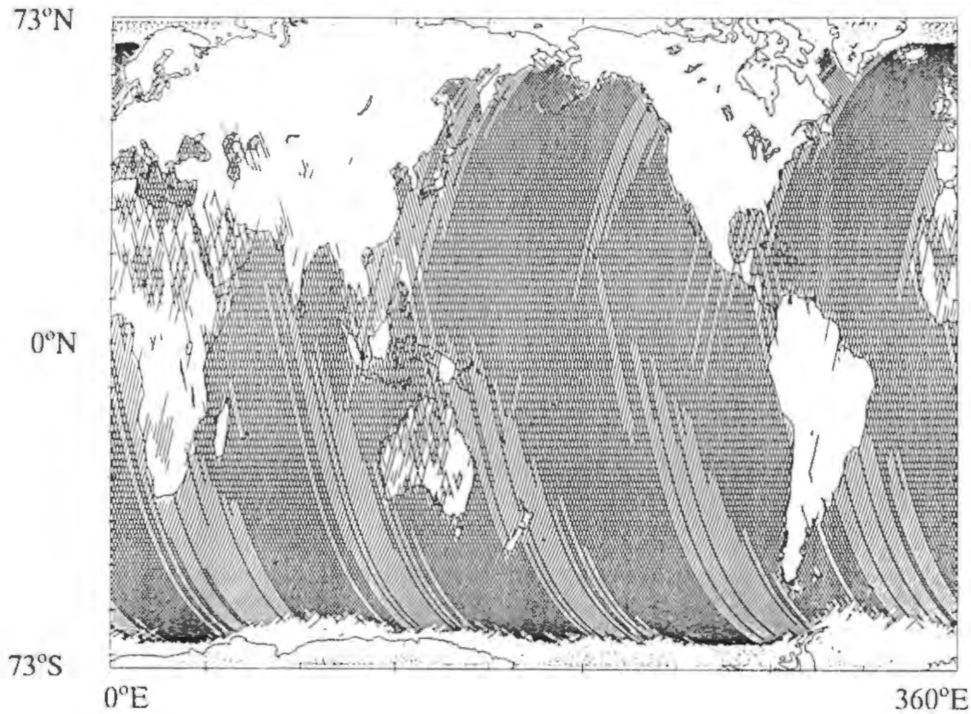
1987



ERM Cycle 12

Days 134-150

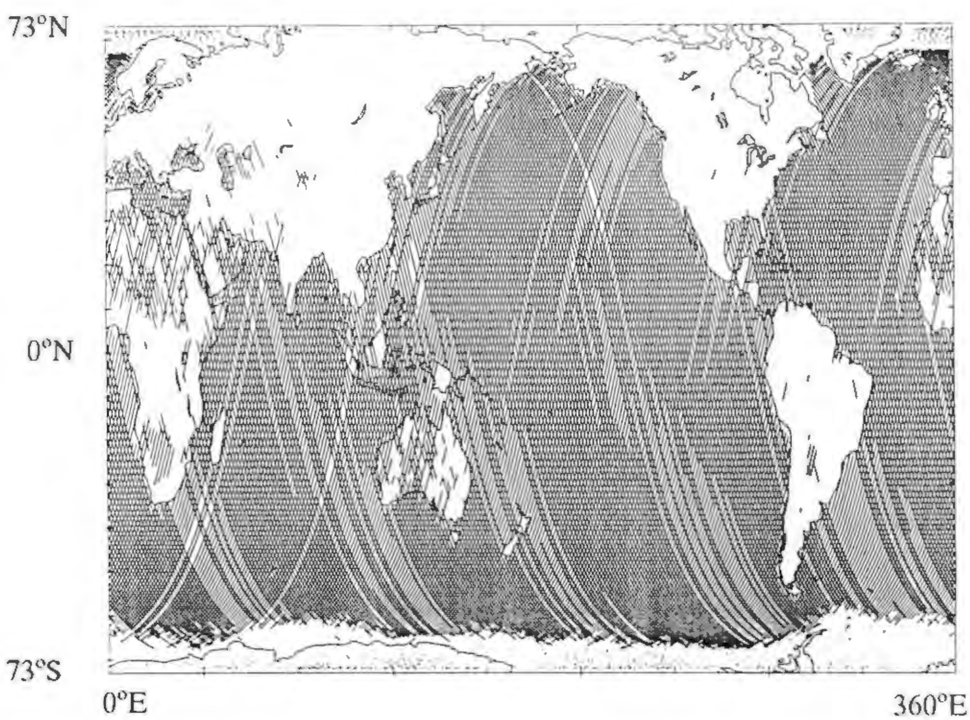
1987



ERM Cycle 13

Days 151-167

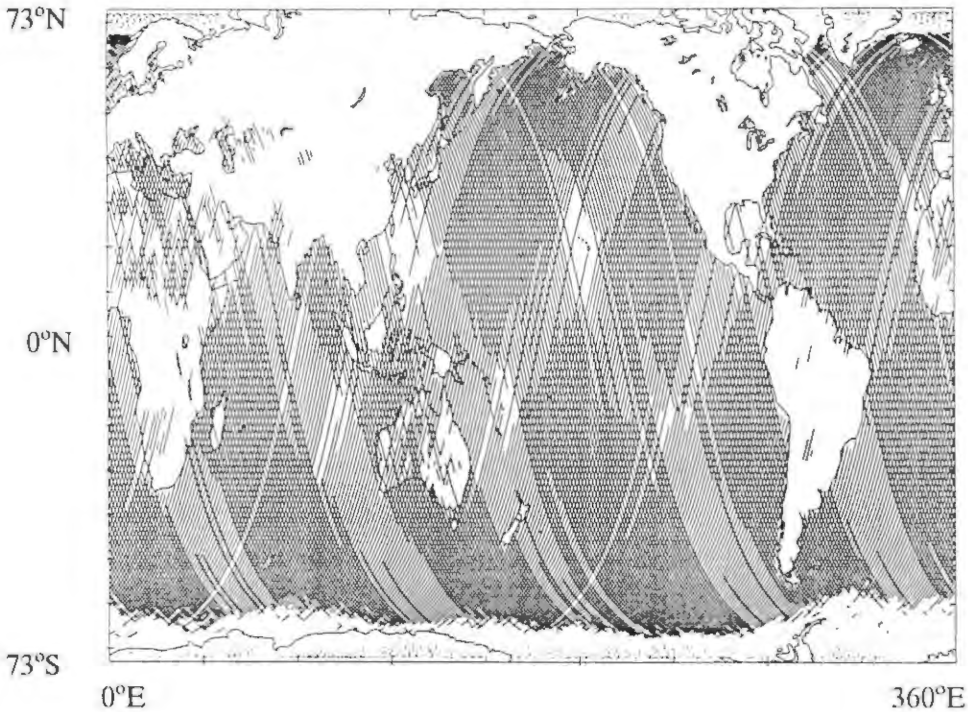
1987



ERM Cycle 14

Days 168-184

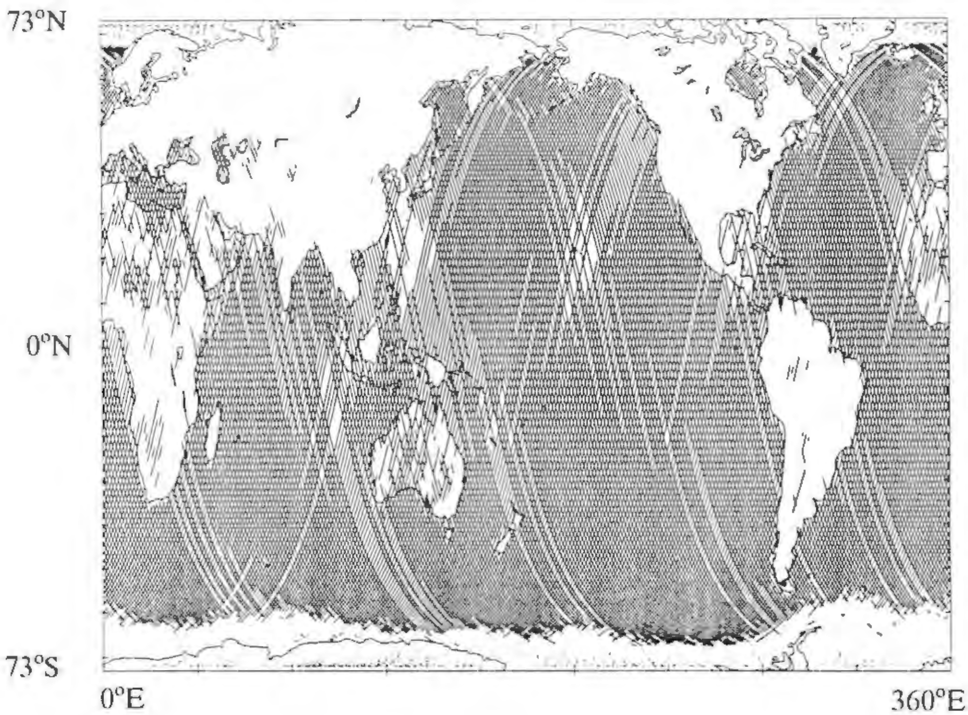
1987



ERM Cycle 15

Days 185-201

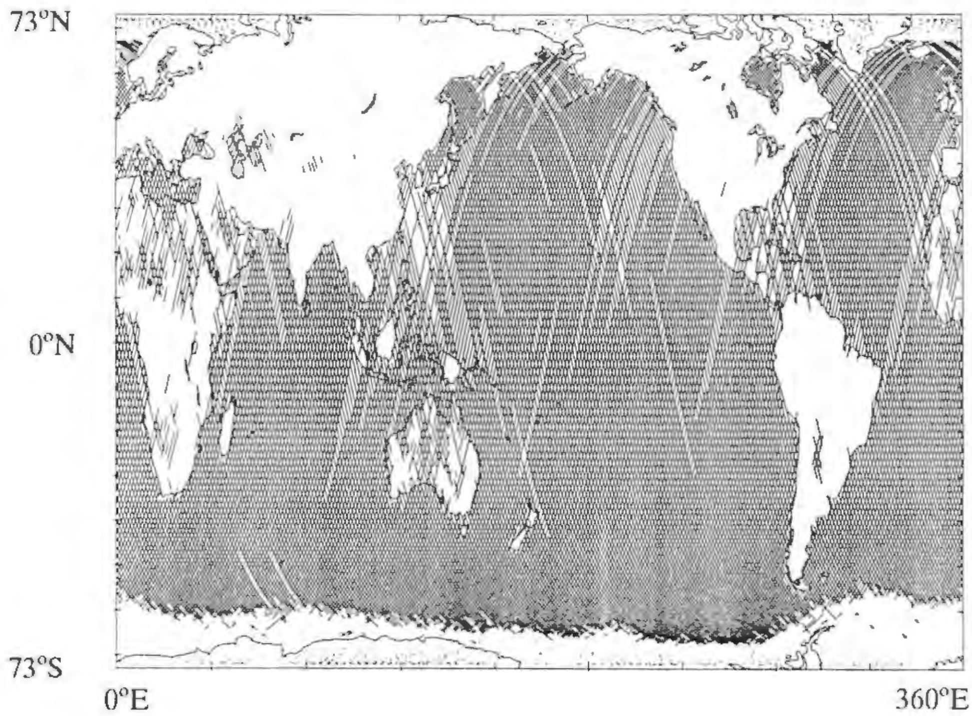
1987



ERM Cycle 16

Days 202-218

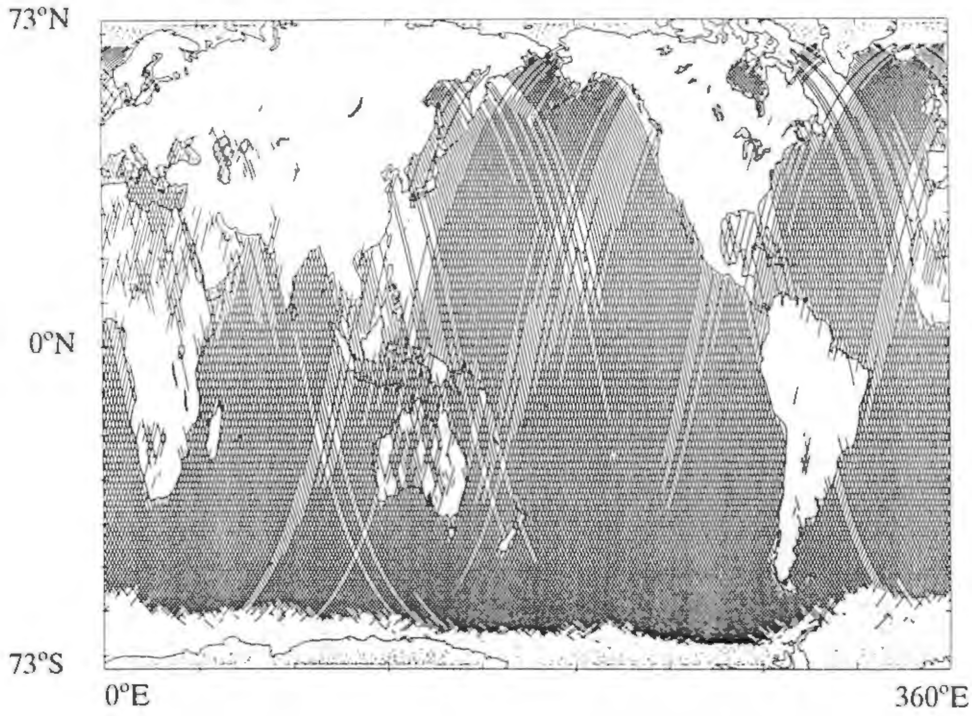
1987



ERM Cycle 17

Days 219-235

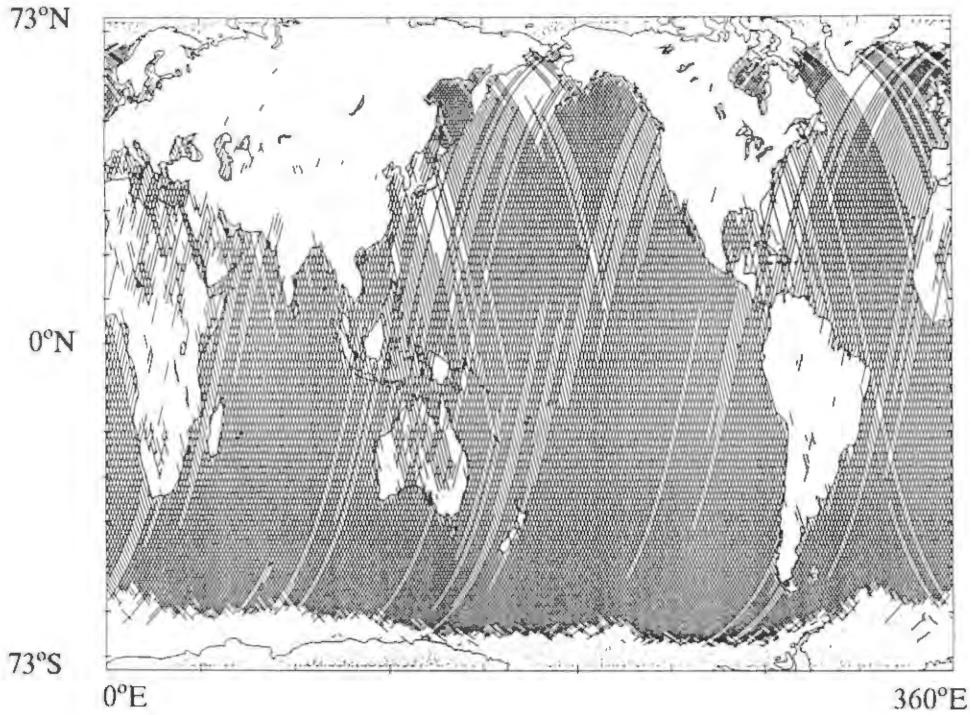
1987



ERM Cycle 18

Days 236-252

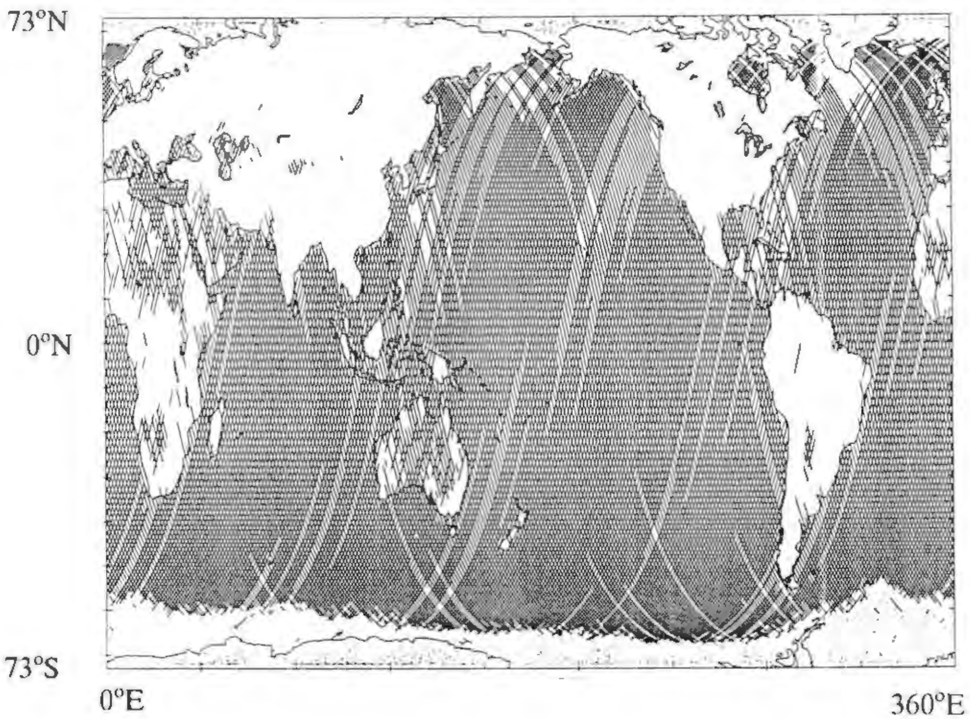
1987



ERM Cycle 19

Days 253-269

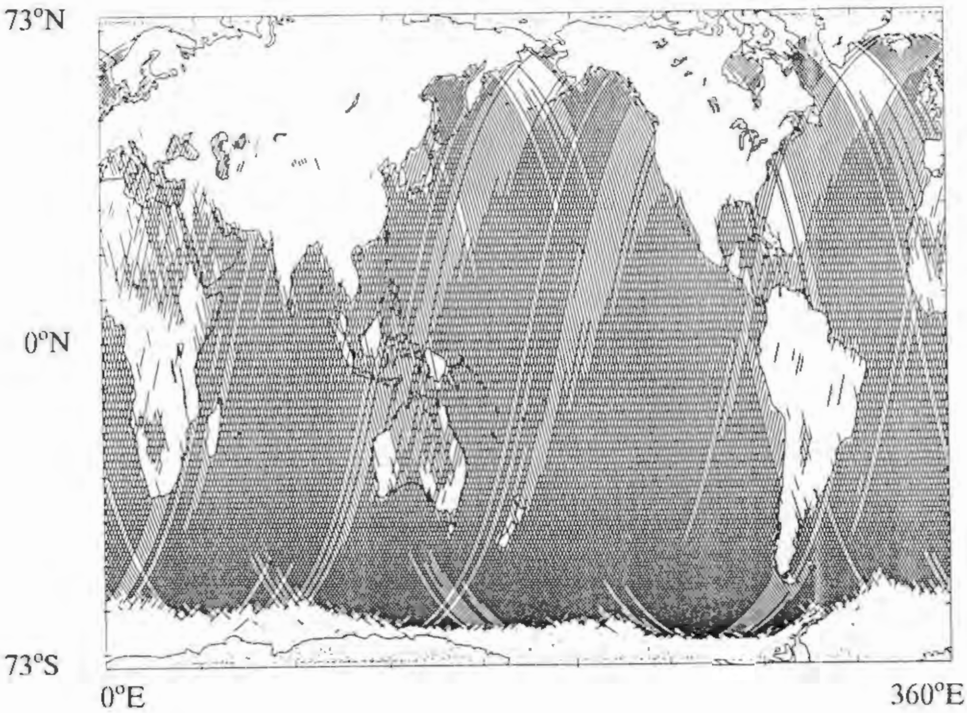
1987



ERM Cycle 20

Days 270-286

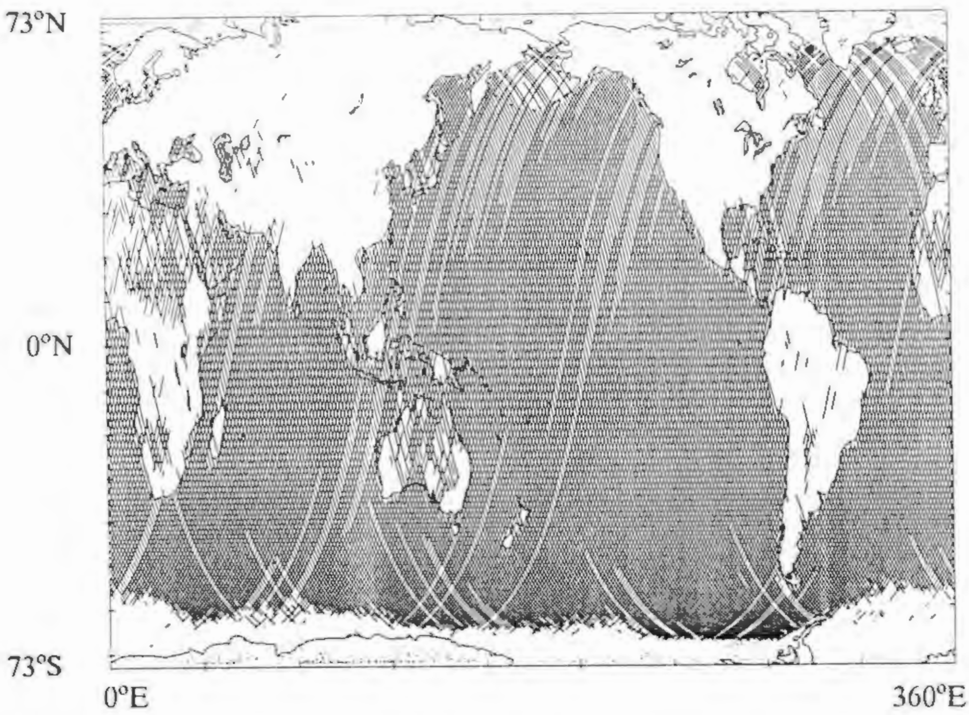
1987



ERM Cycle 21

Days 287-303

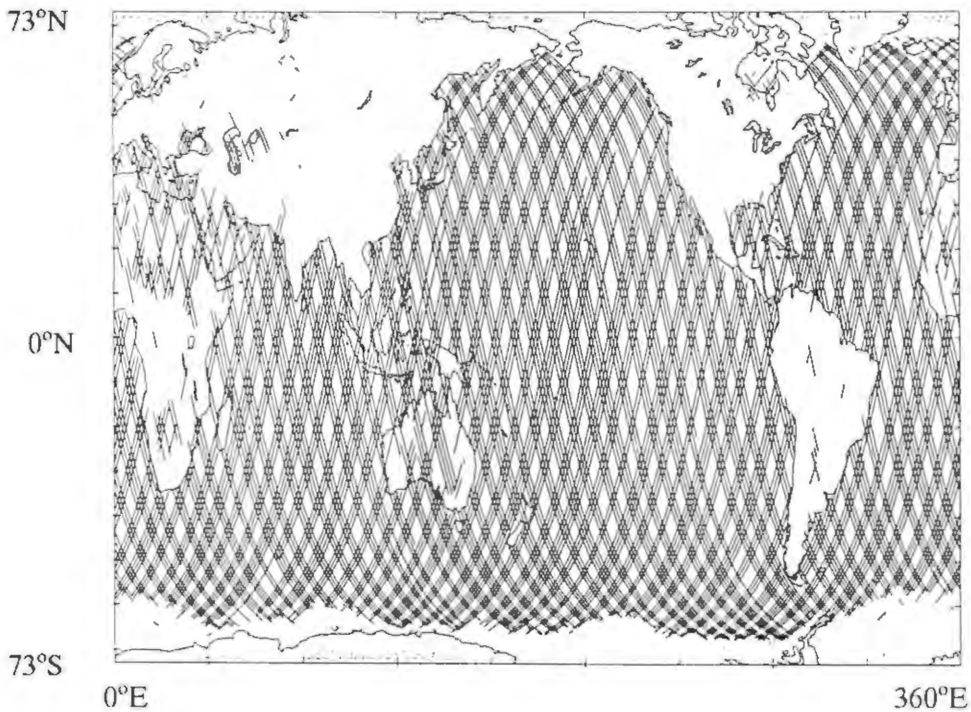
1987



ERM Cycle 22

Days 304-320

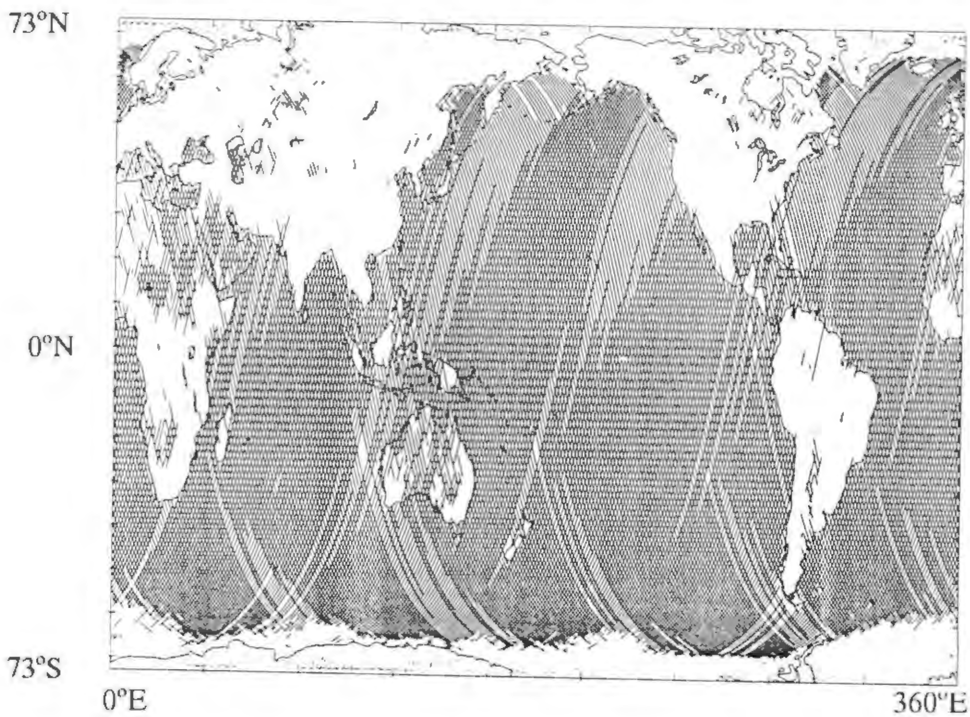
1987



ERM Cycle 23

Days 321-337

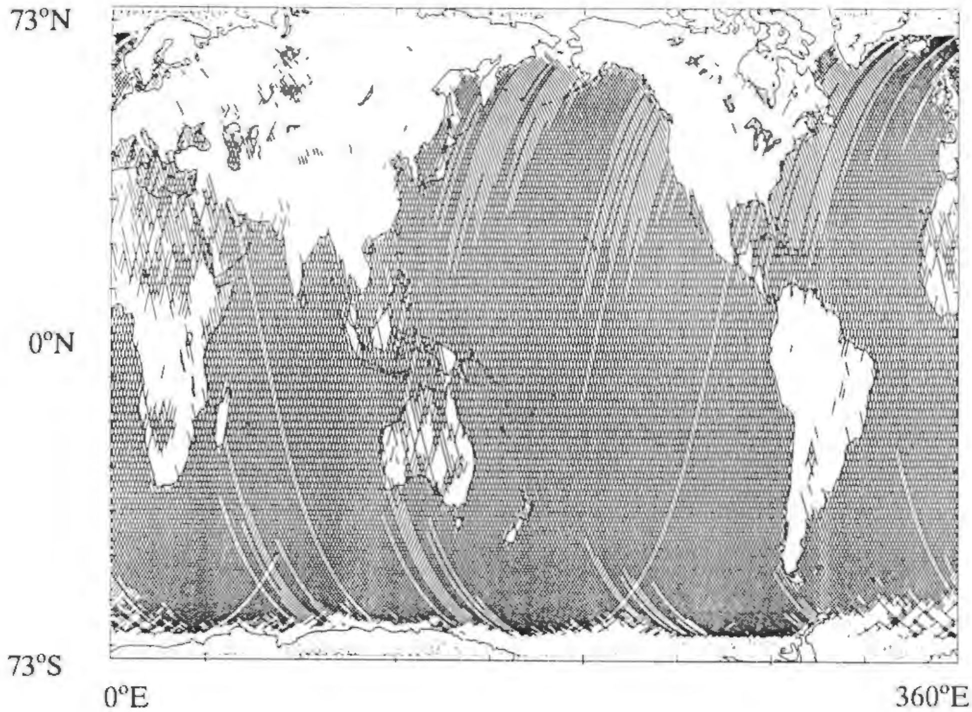
1987



ERM Cycle 24

Days 338-354

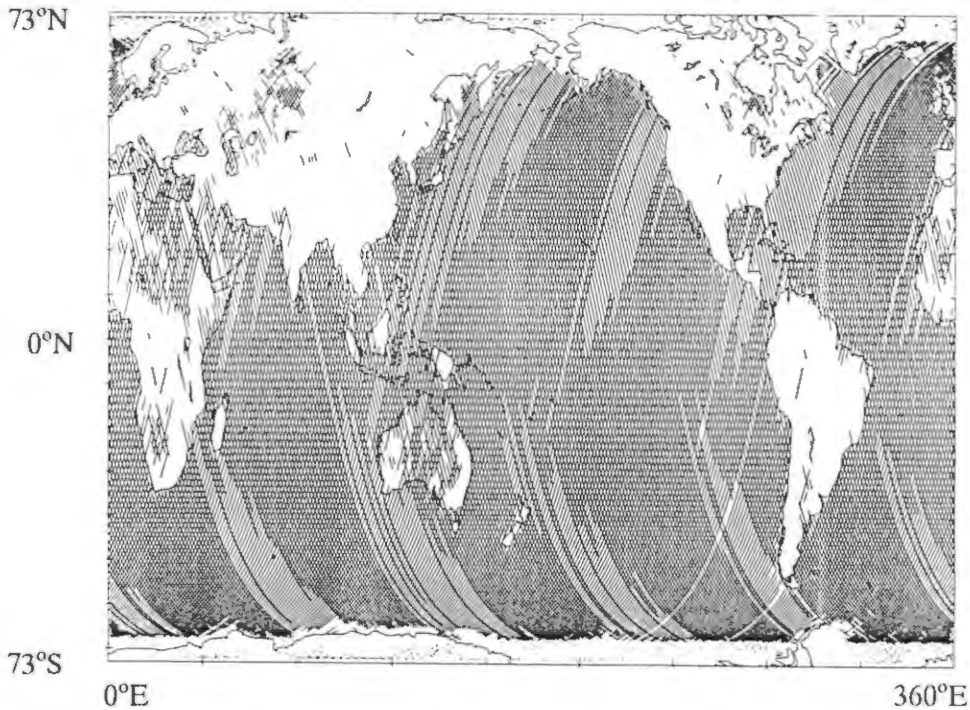
1987



ERM Cycle 25

Days 355-006

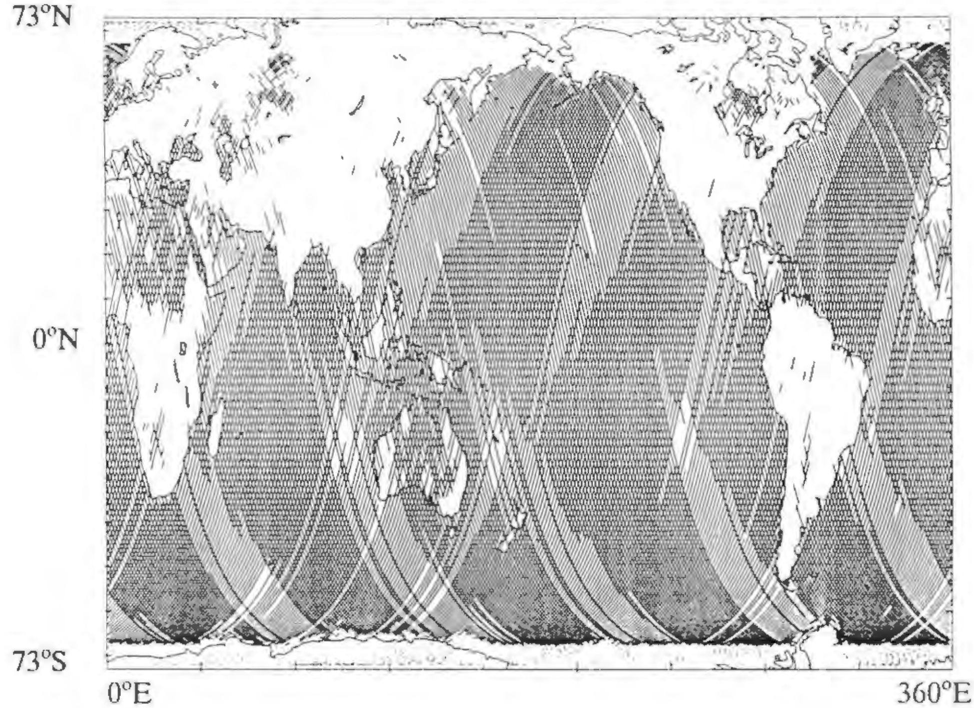
1987-88



ERM Cycle 26

Days 007-023

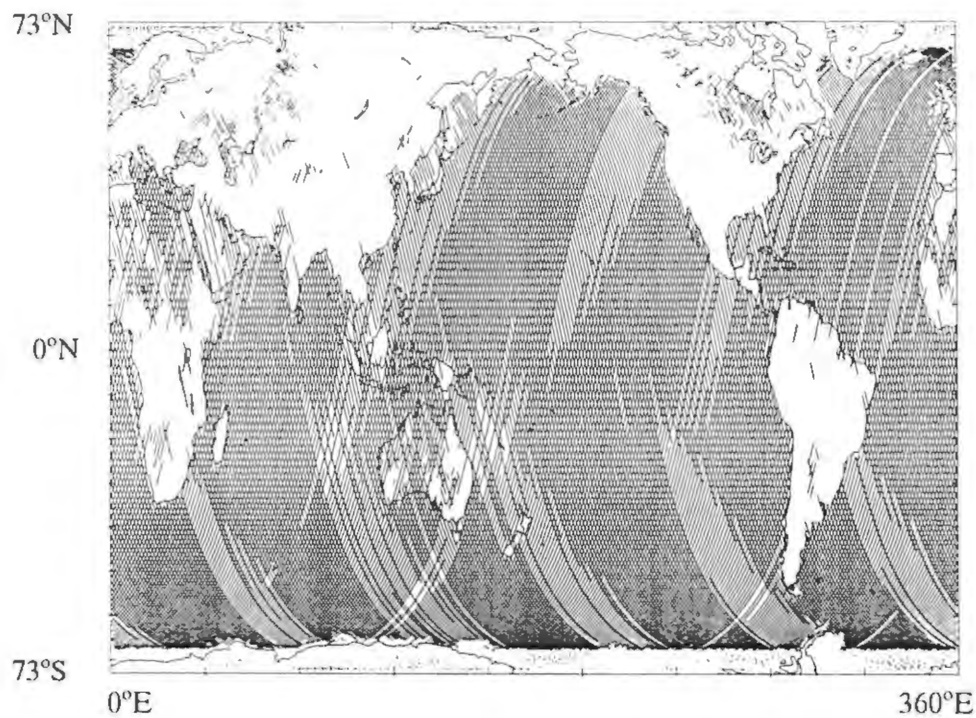
1988



ERM Cycle 27

Days 024-040

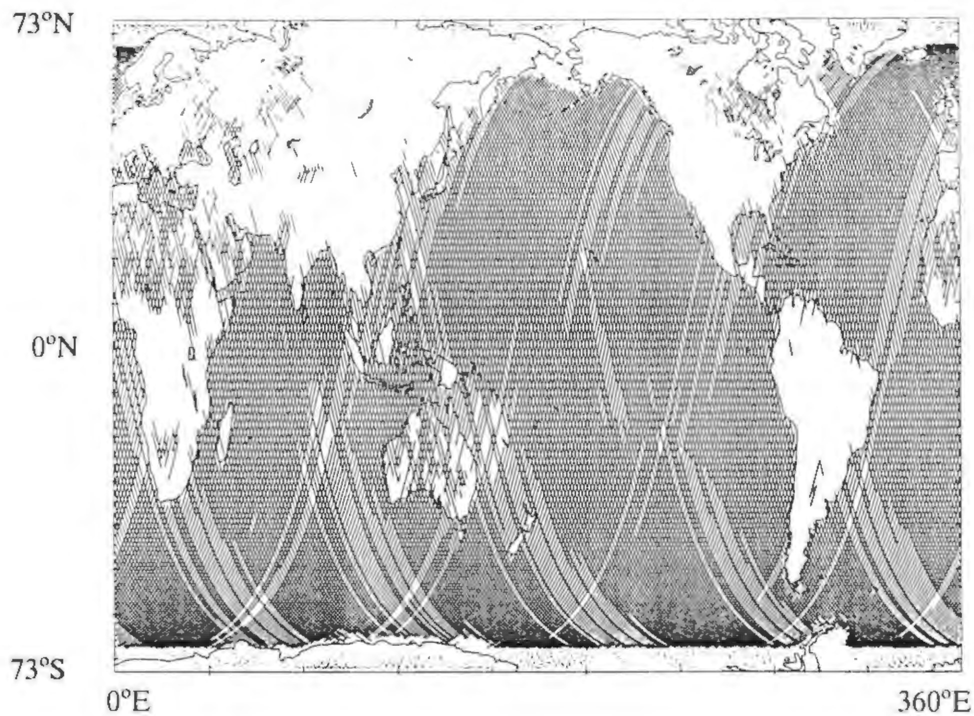
1988



ERM Cycle 28

Days 041-057

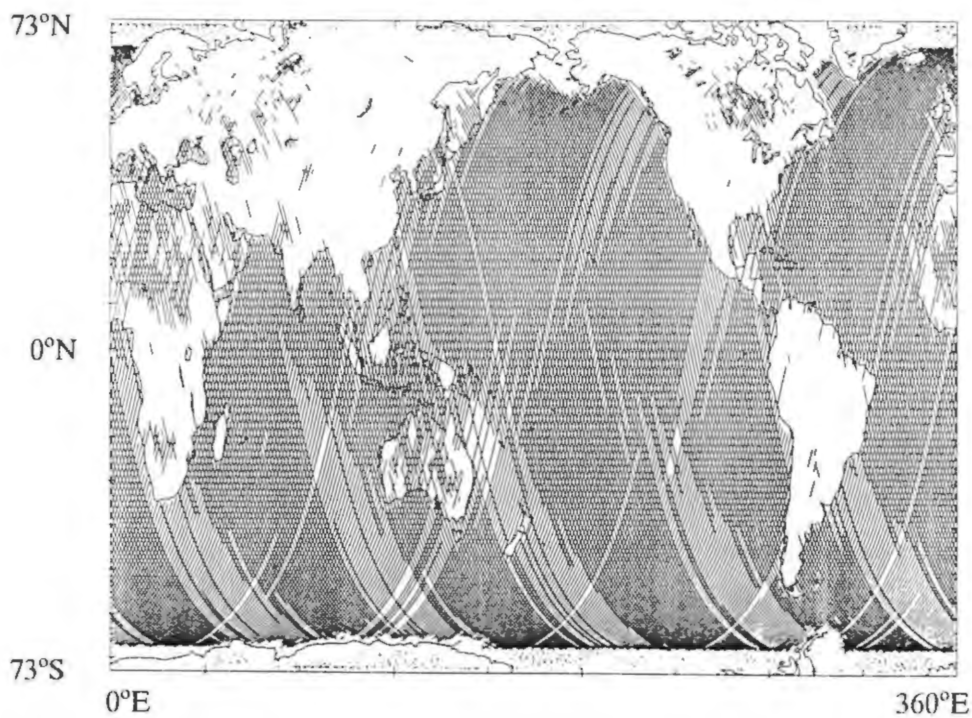
1988



ERM Cycle 29

Days 058-074

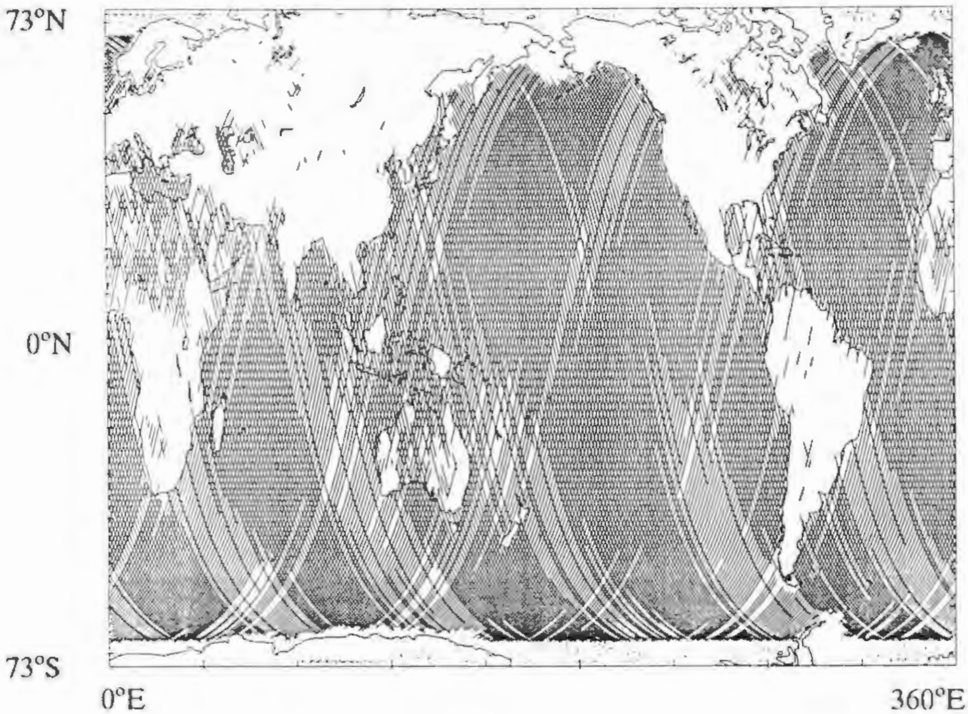
1988



ERM Cycle 30

Days 075-091

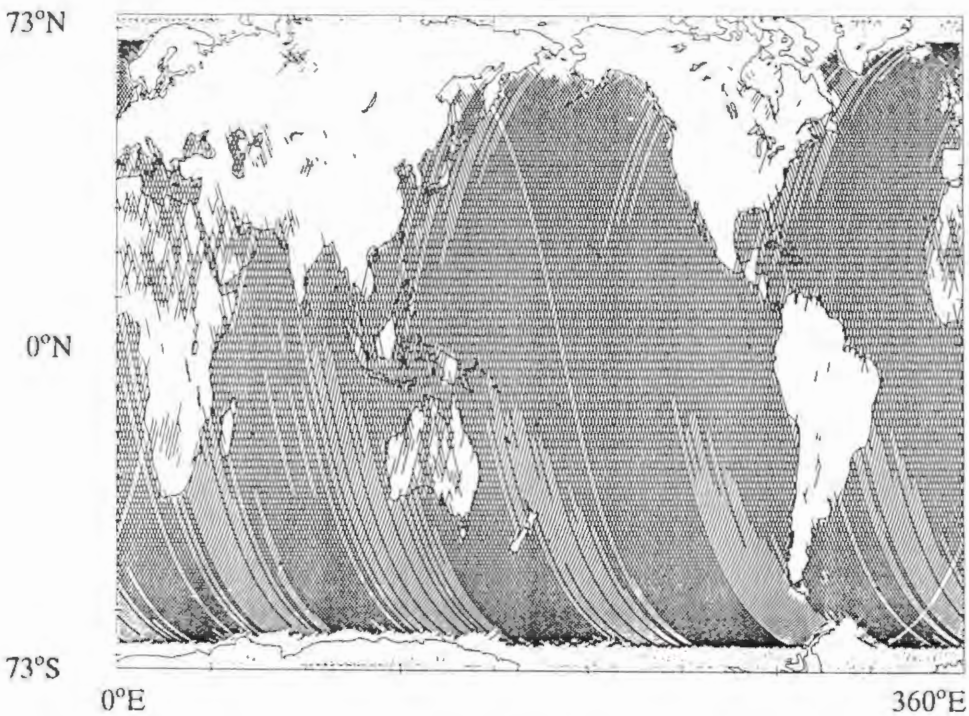
1988



ERM Cycle 31

Days 092-108

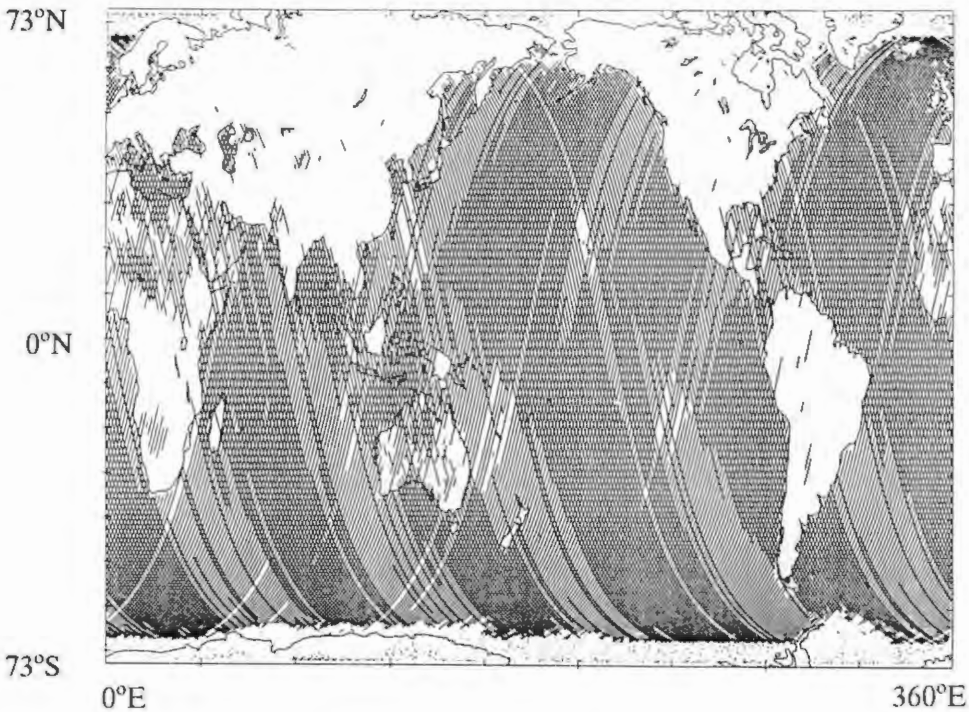
1988



ERM Cycle 32

Days 109-125

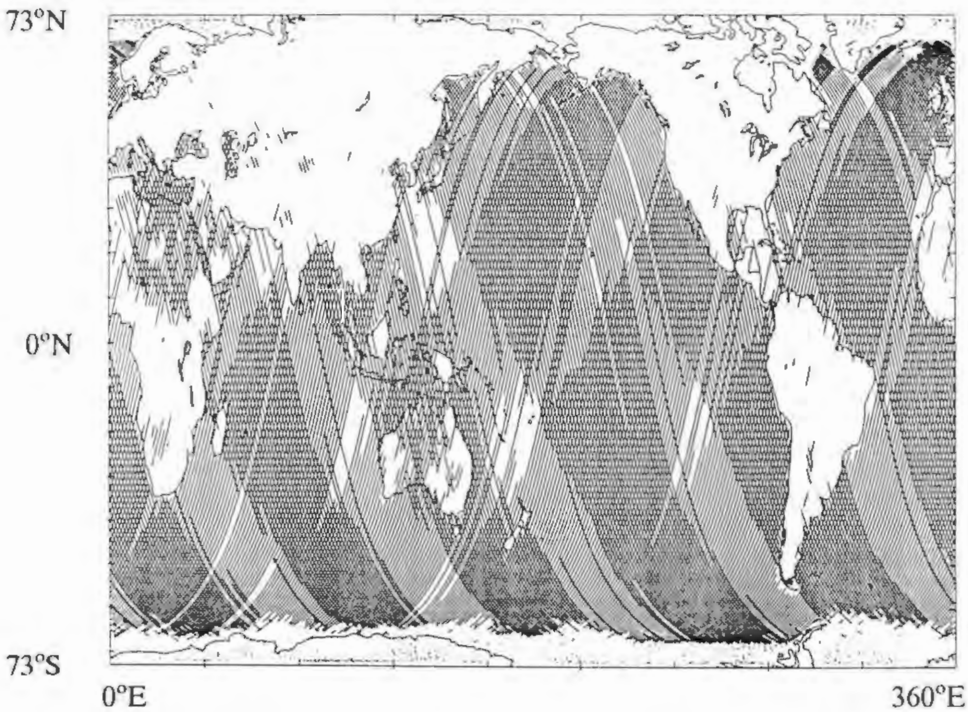
1988



ERM Cycle 33

Days 126-142

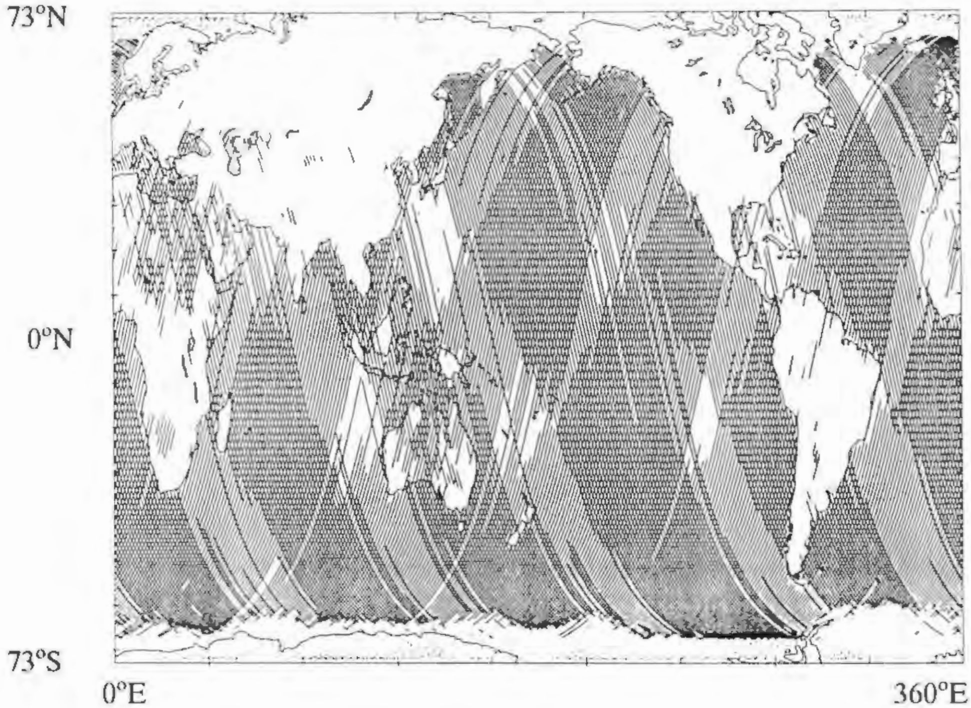
1988



ERM Cycle 34

Days 143-159

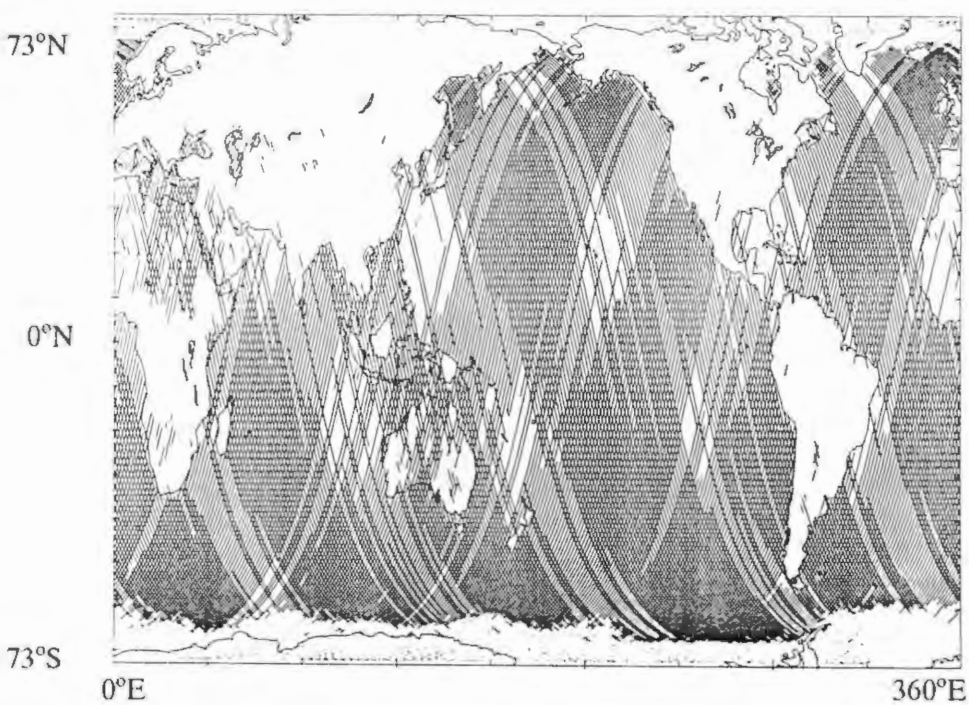
1988



ERM Cycle 35

Days 160-176

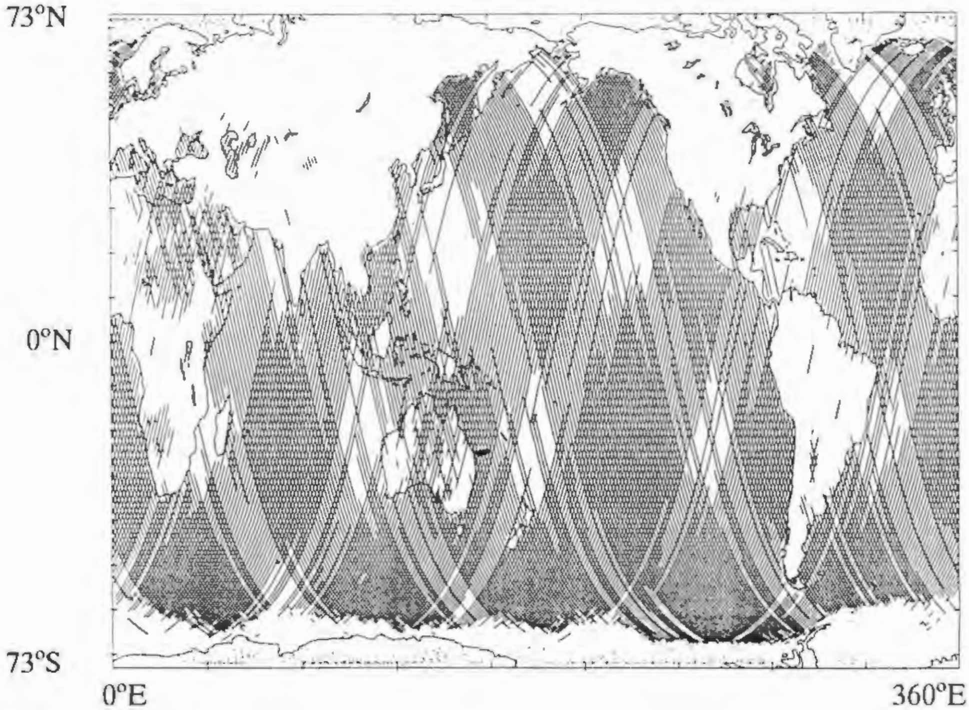
1988



ERM Cycle 36

Days 177-193

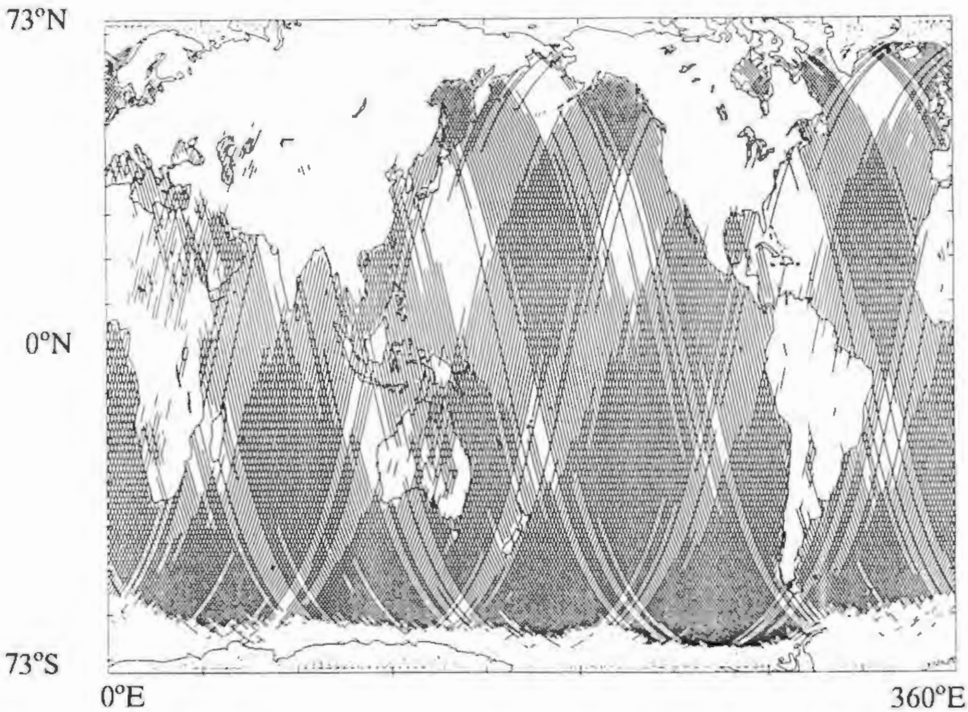
1988



ERM Cycle 37

Days 194-210

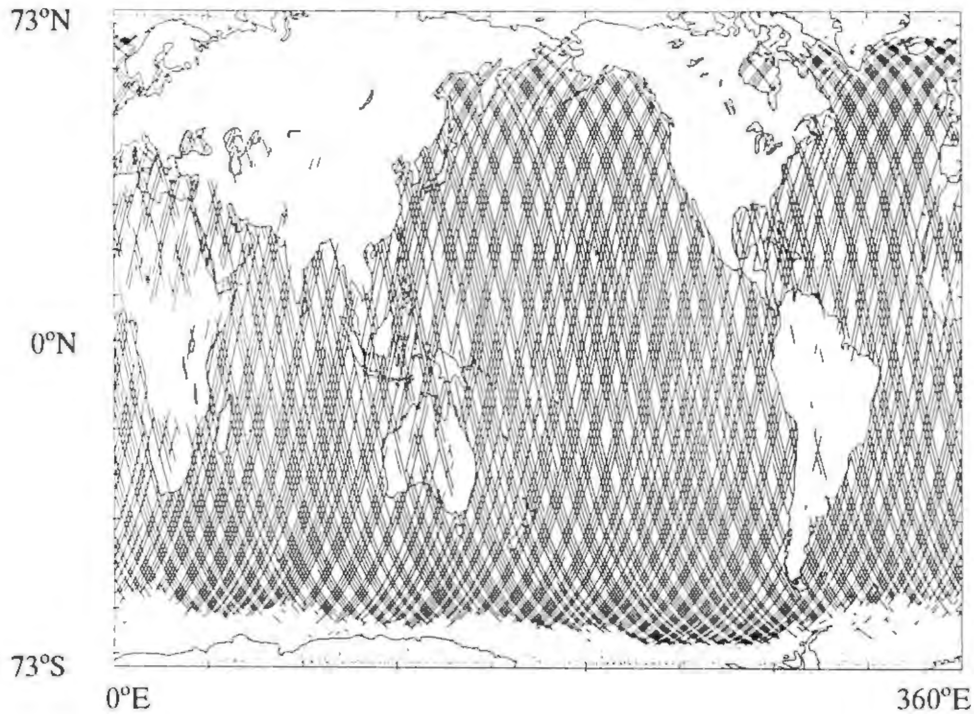
1988



ERM Cycle 38

Days 211-227

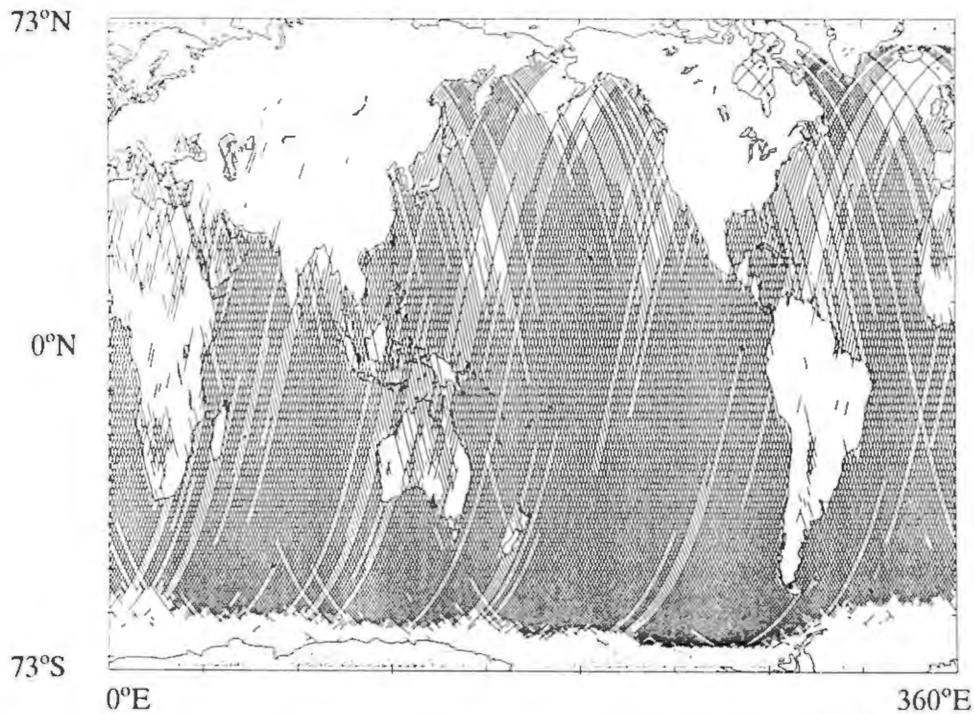
1988



ERM Cycle 39

Days 228-244

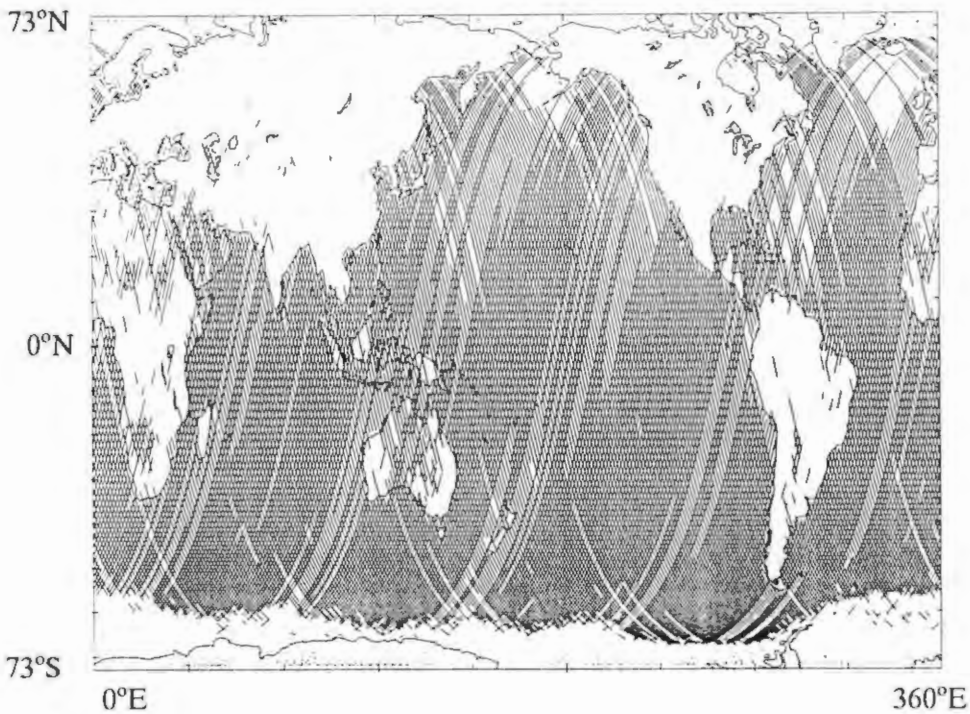
1988



ERM Cycle 40

Days 245-261

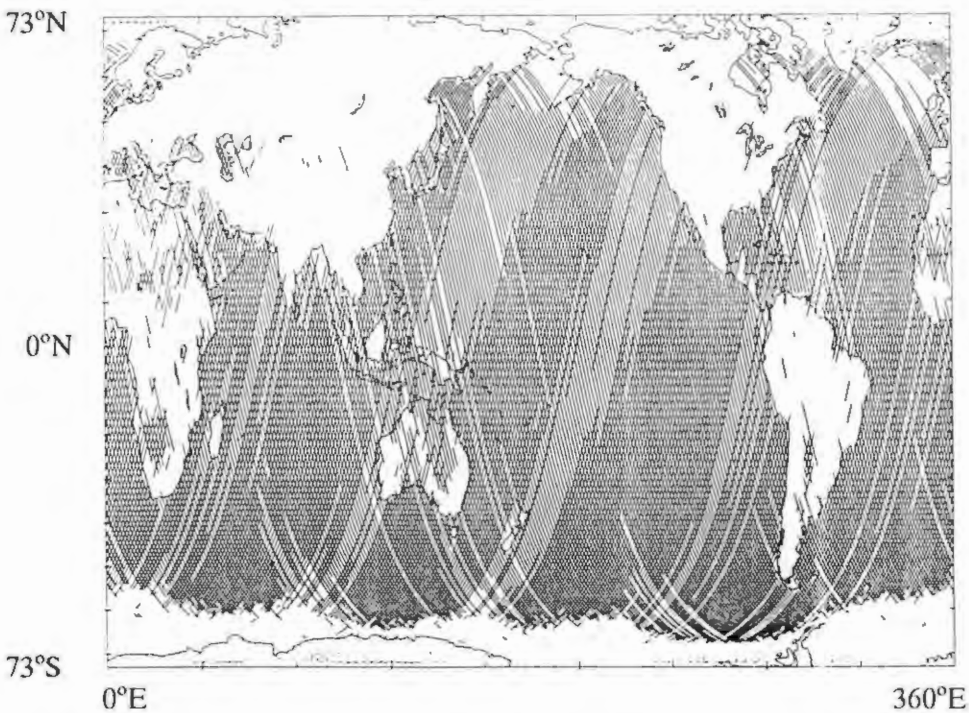
1988



ERM Cycle 41

Days 262-278

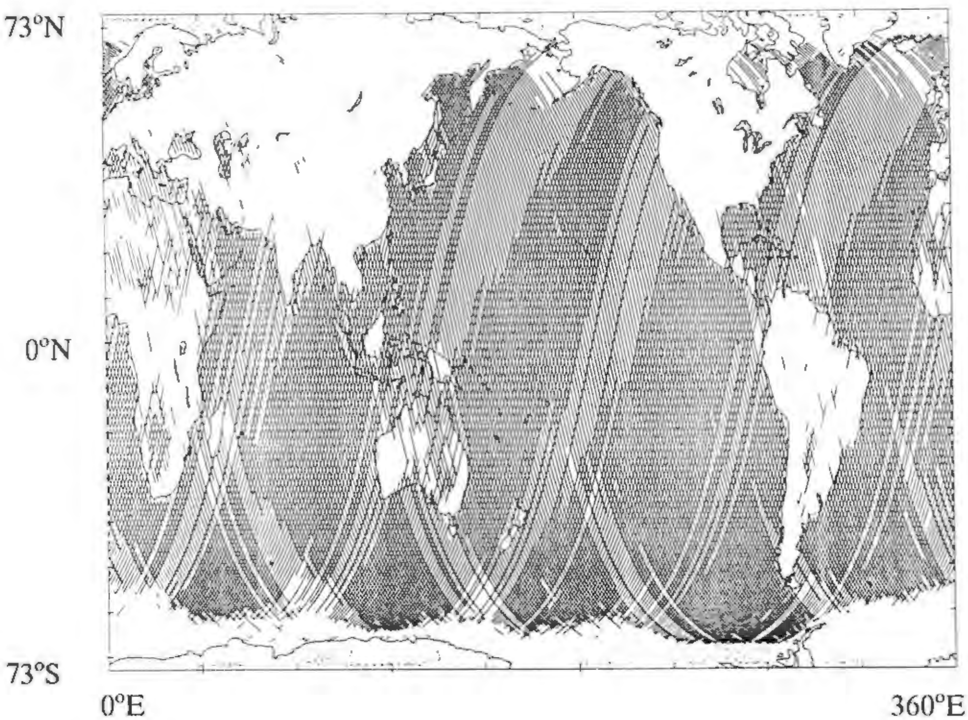
1988



ERM Cycle 42

Days 279-295

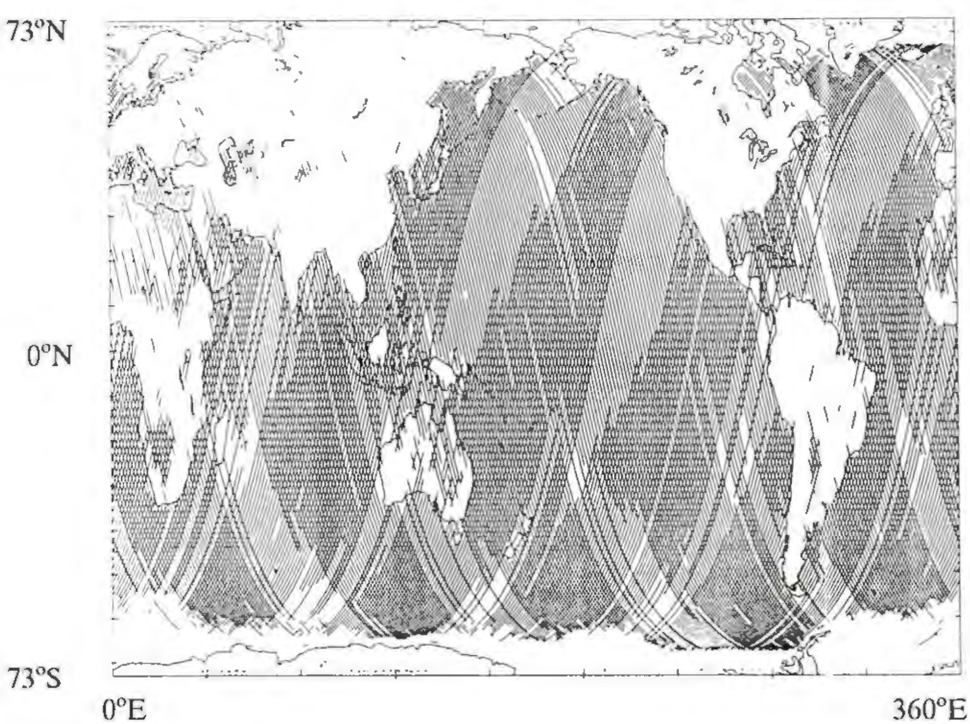
1988



ERM Cycle 43

Days 296-312

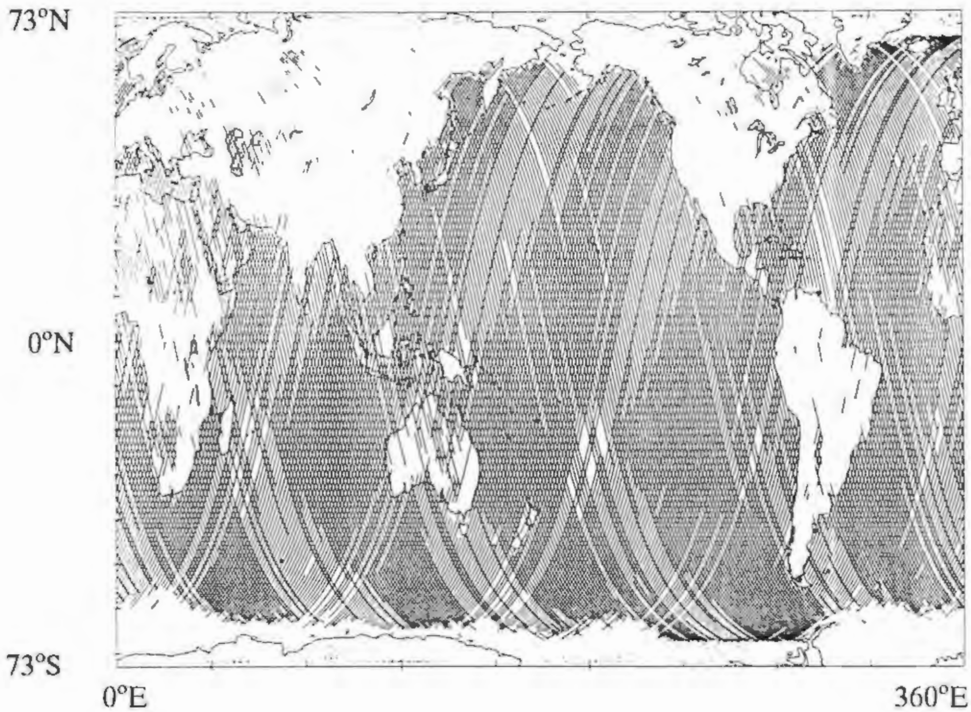
1988



ERM Cycle 44

Days 313-329

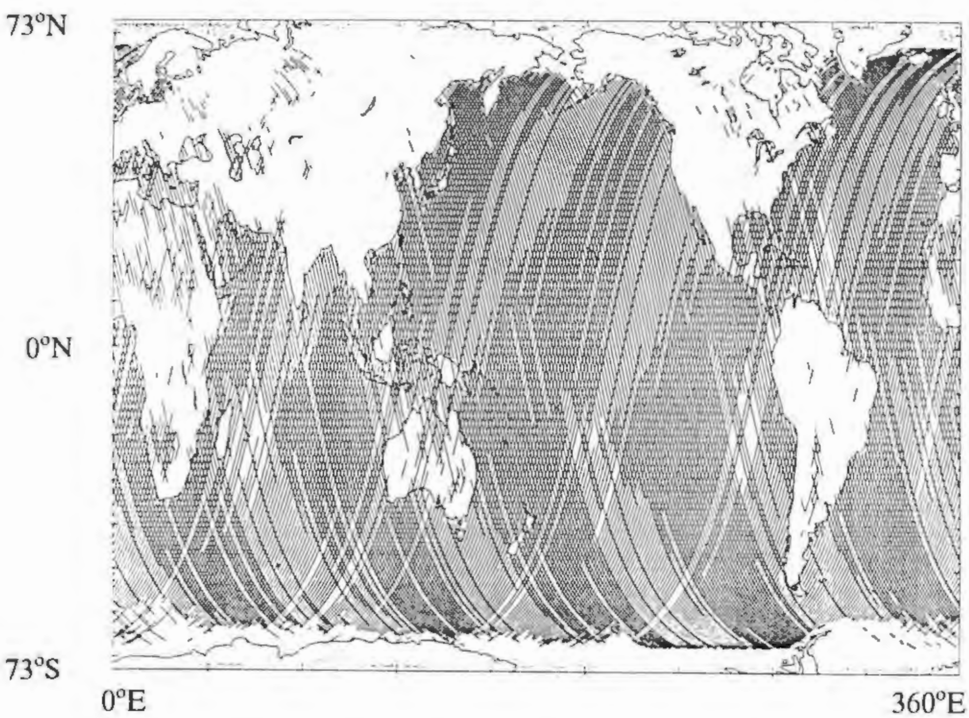
1988



ERM Cycle 45

Days 330-346

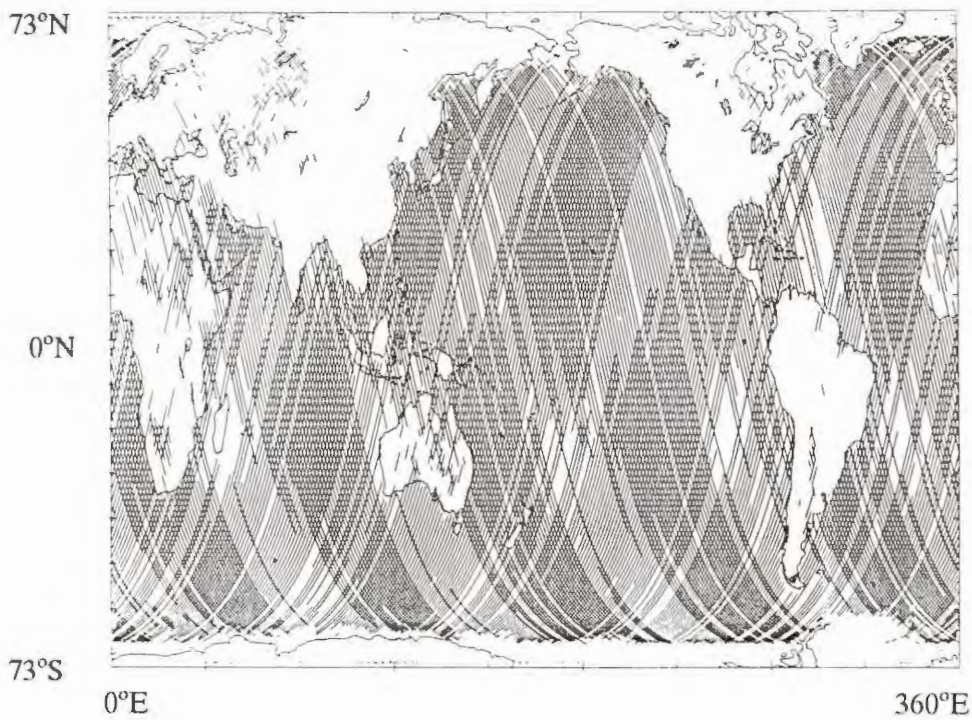
1988



ERM Cycle 46

Days 347-363

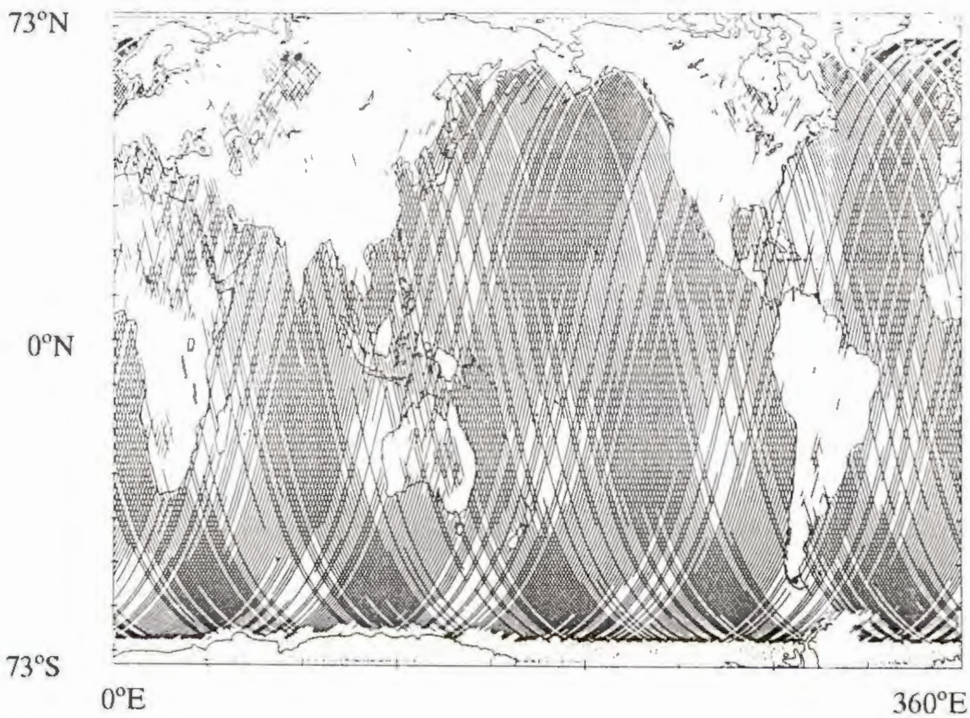
1988



ERM Cycle 47

Days 364-014

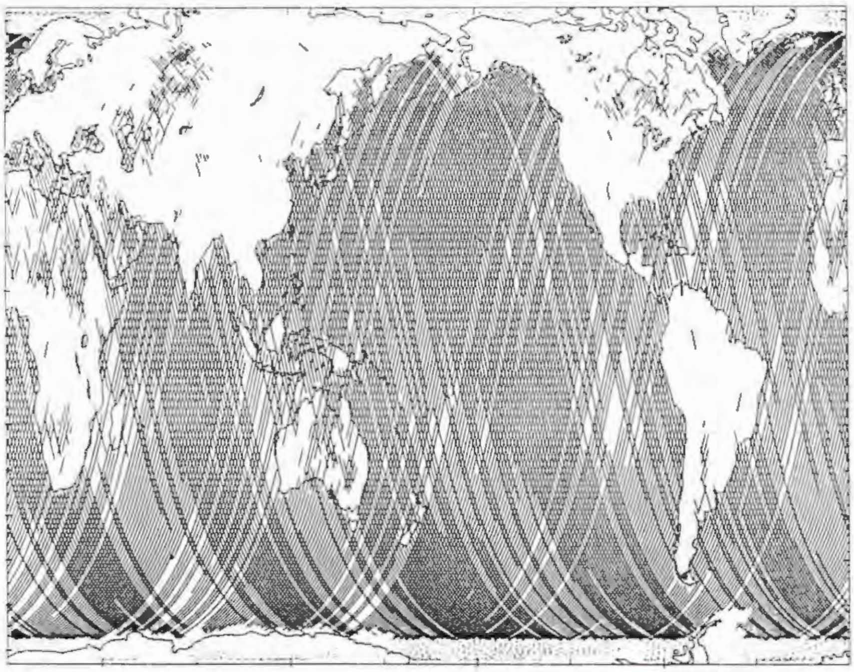
1988-89



ERM Cycle 48

Days 015-031

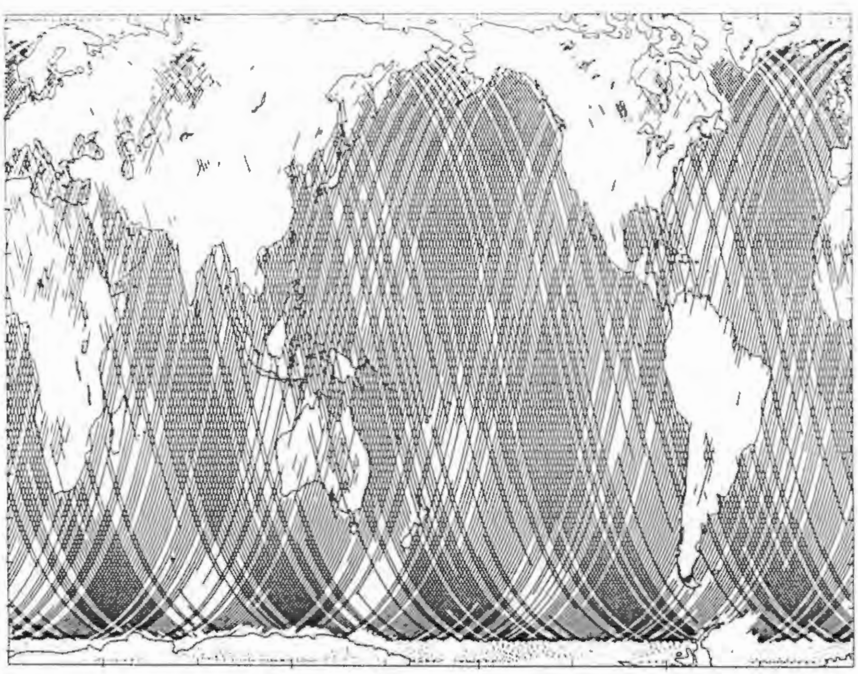
1989



ERM Cycle 49

Days 032-048

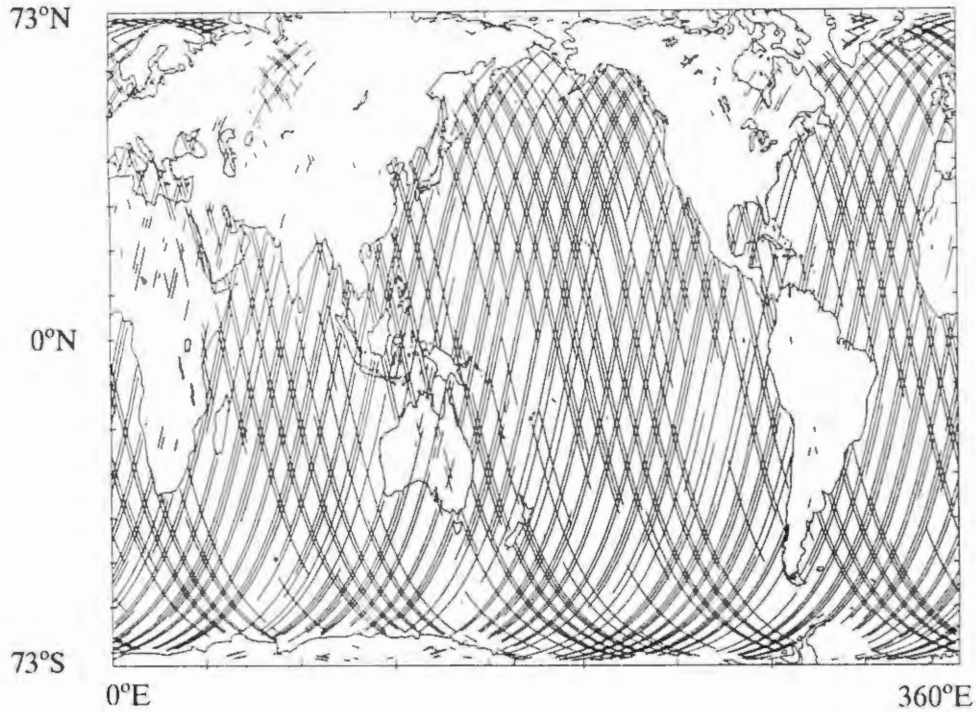
1989



ERM Cycle 50

Days 049-065

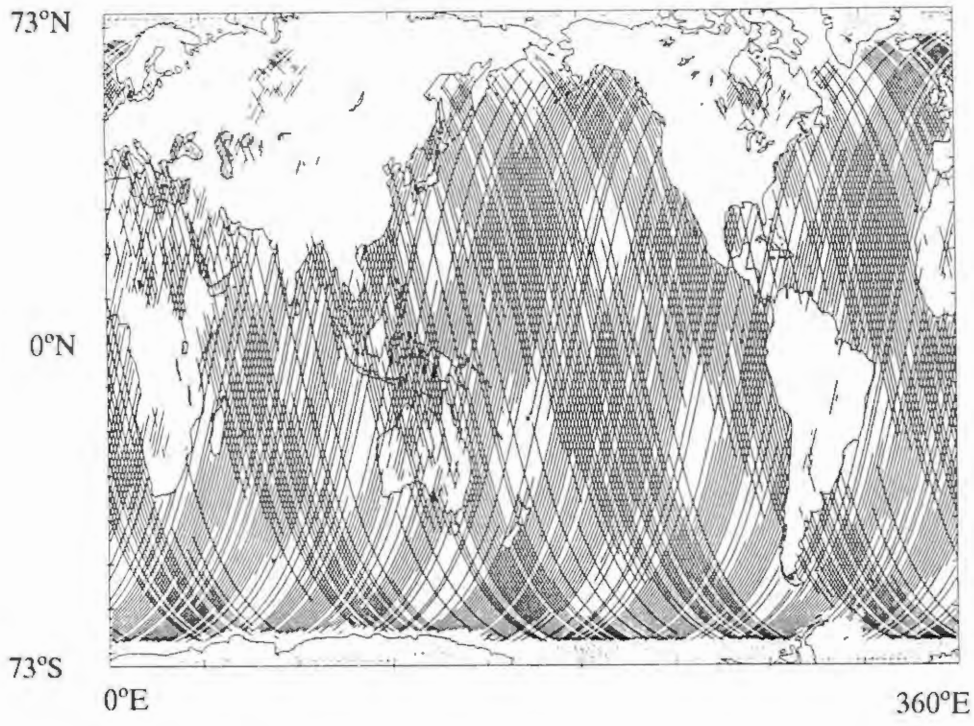
1989



ERM Cycle 51

Days 066-082

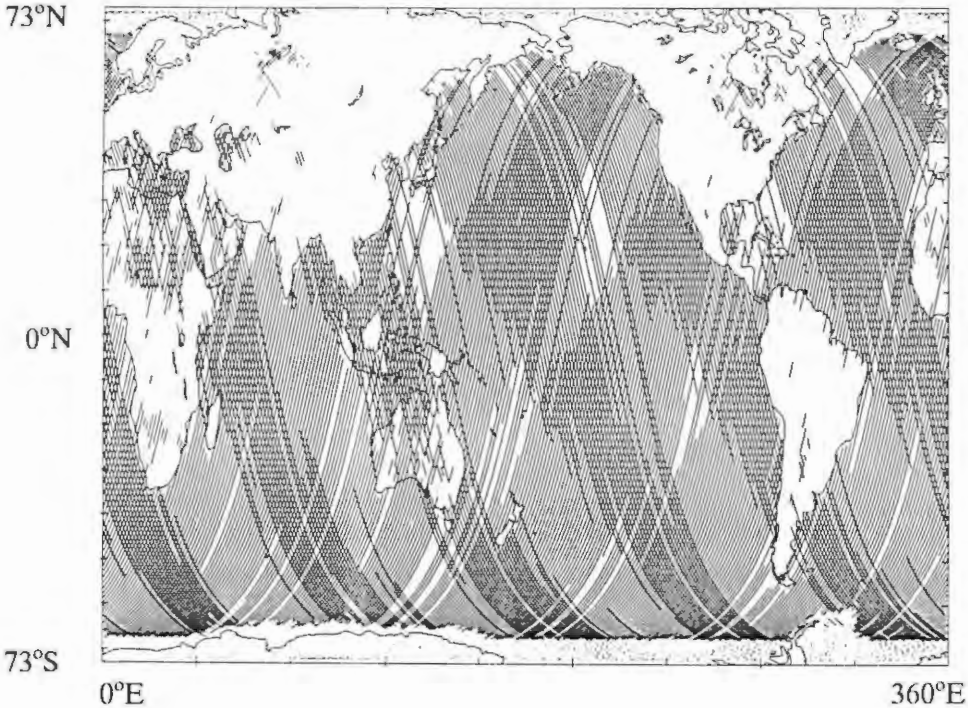
1989



ERM Cycle 52

Days 083-099

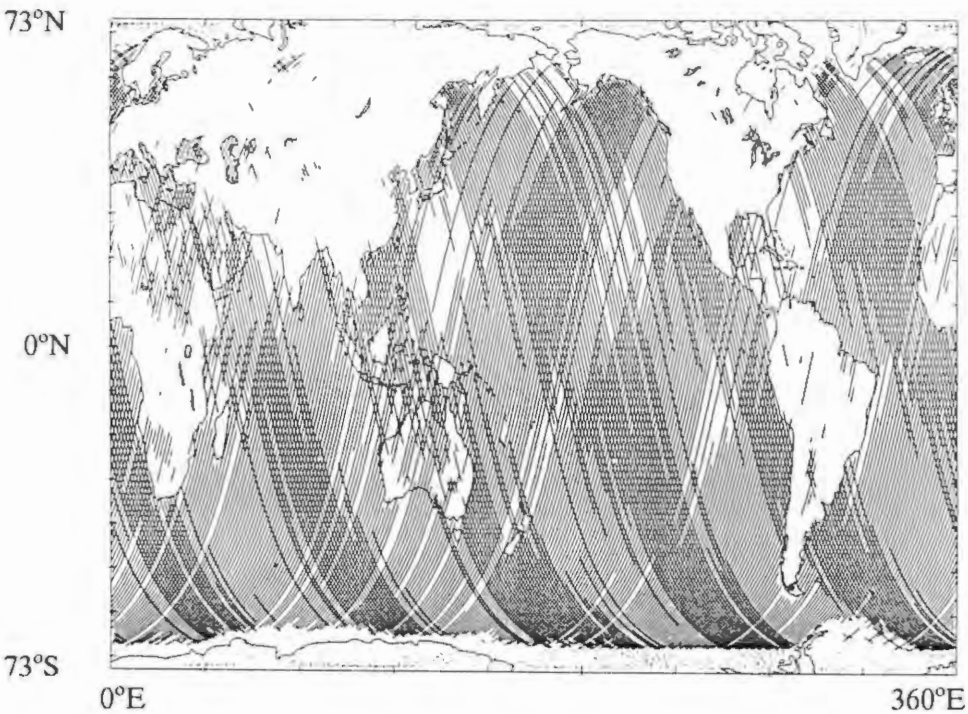
1989



ERM Cycle 53

Days 100-116

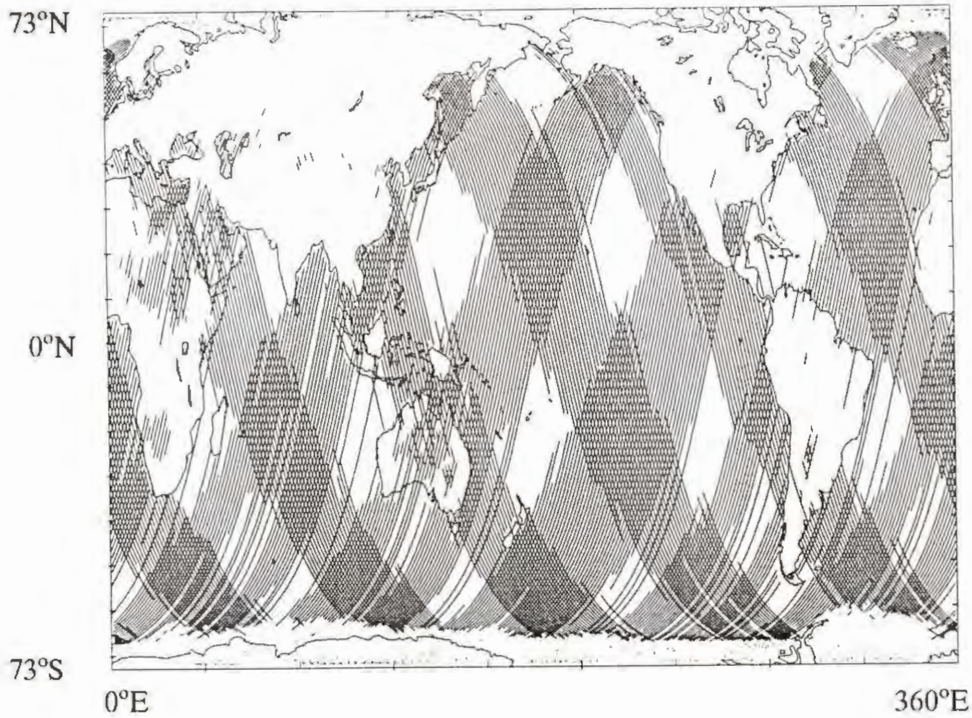
1989



ERM Cycle 54

Days 117-133

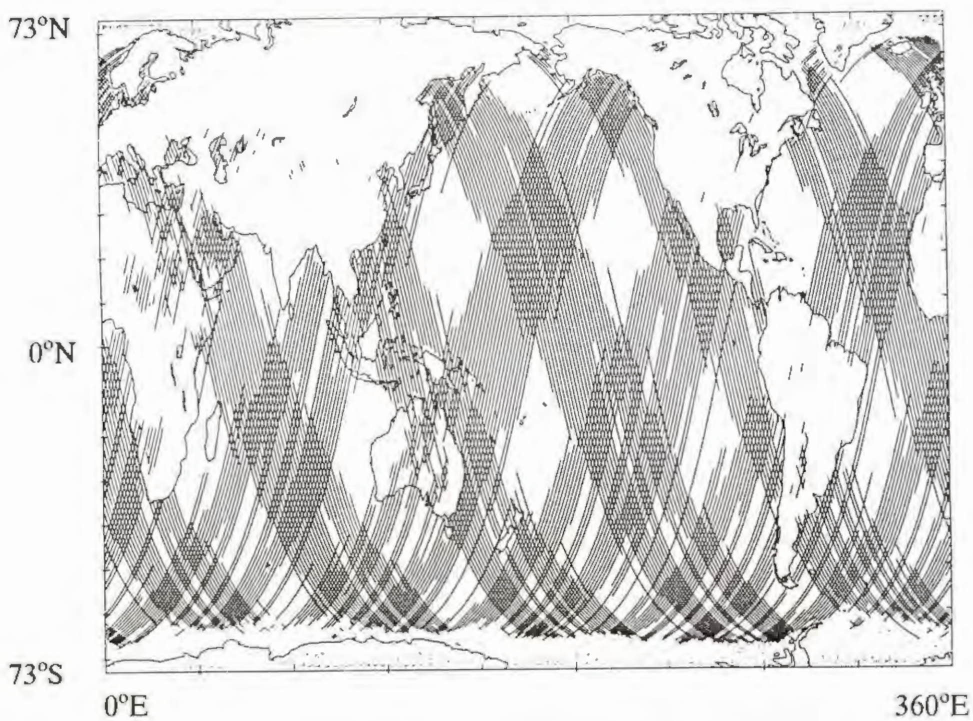
1989



ERM Cycle 55

Days 134-150

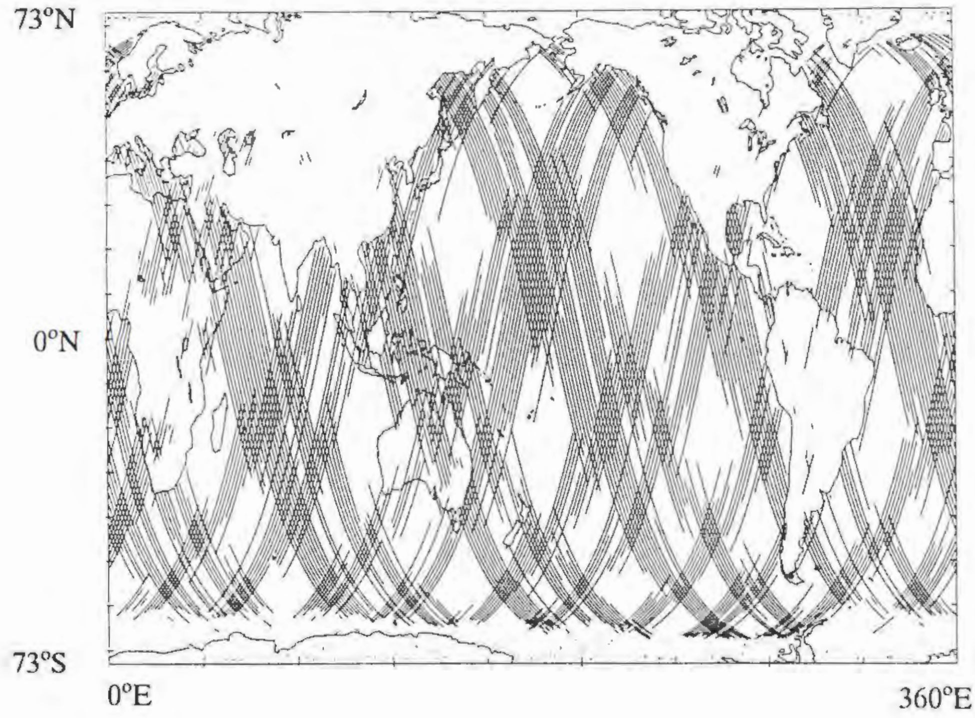
1989



ERM Cycle 56

Days 151-167

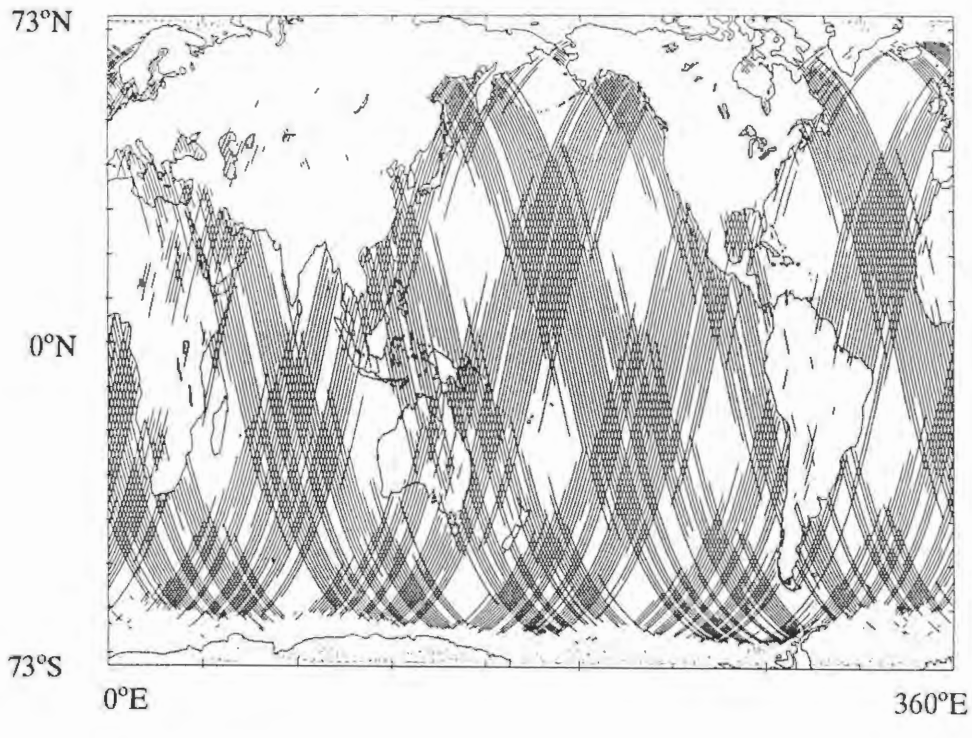
1989



ERM Cycle 57

Days 168-184

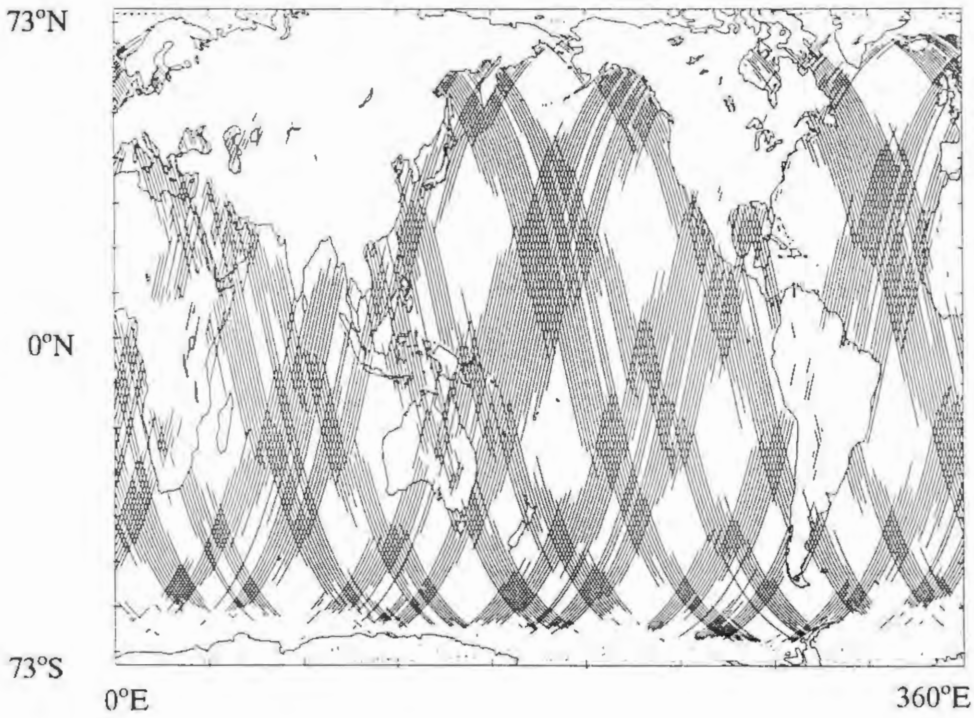
1989



ERM Cycle 58

Days 185-201

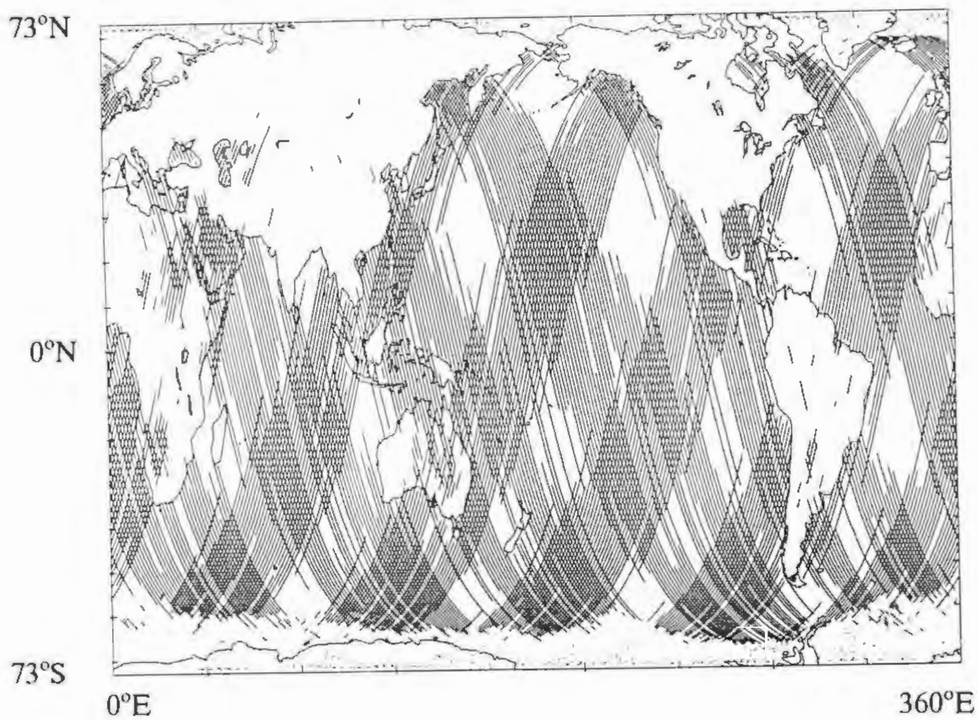
1989



ERM Cycle 59

Days 202-218

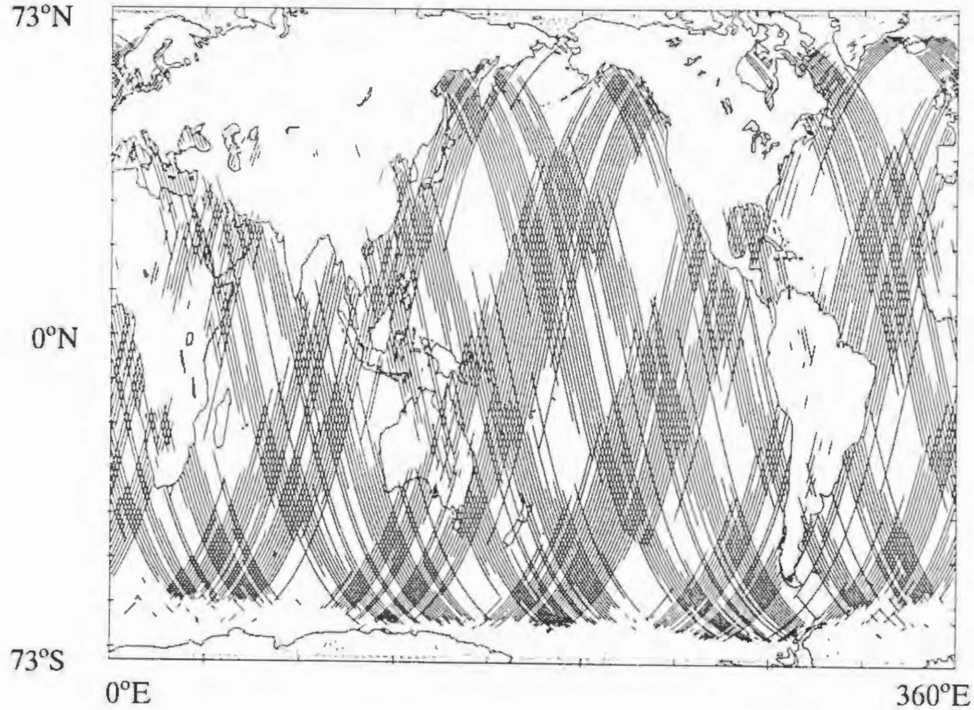
1989



ERM Cycle 60

Days 219-235

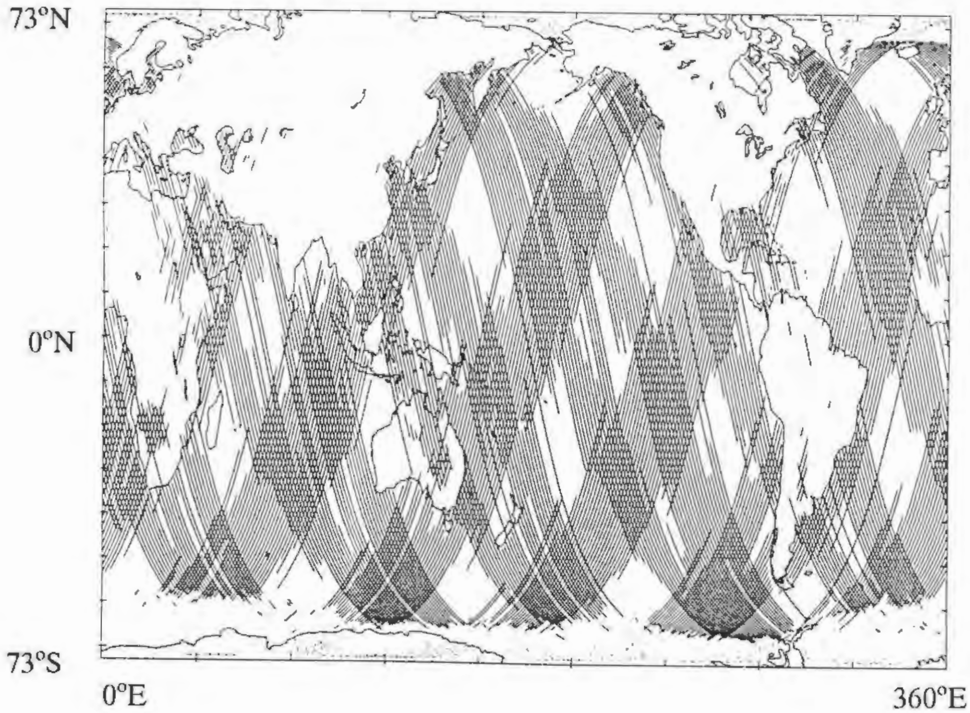
1989



ERM Cycle 61

Days 236-252

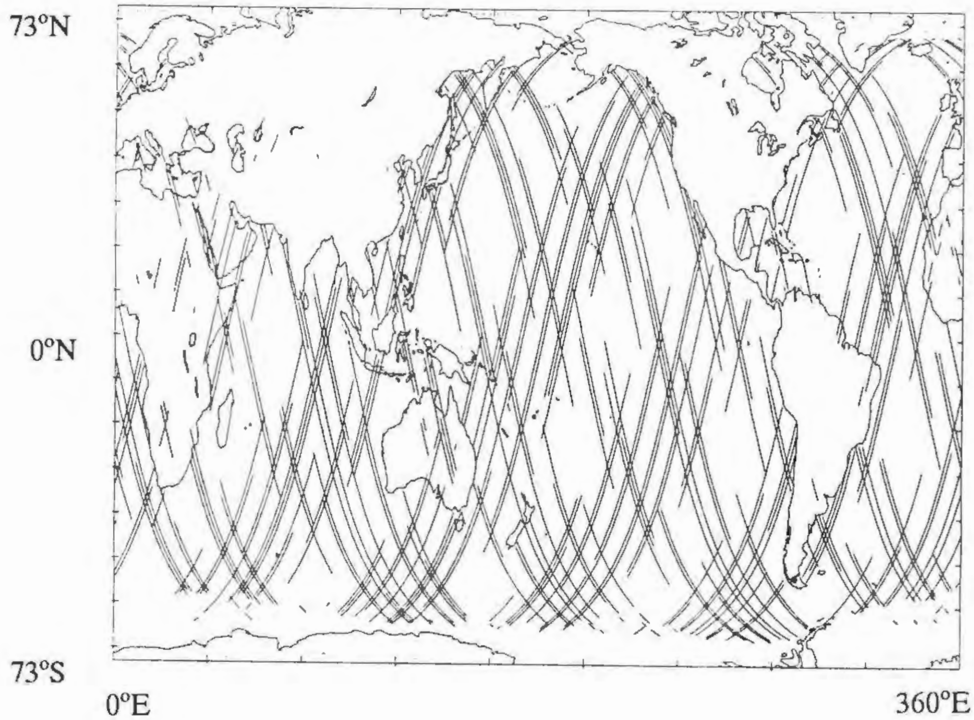
1989



ERM Cycle 62

Days 253-269

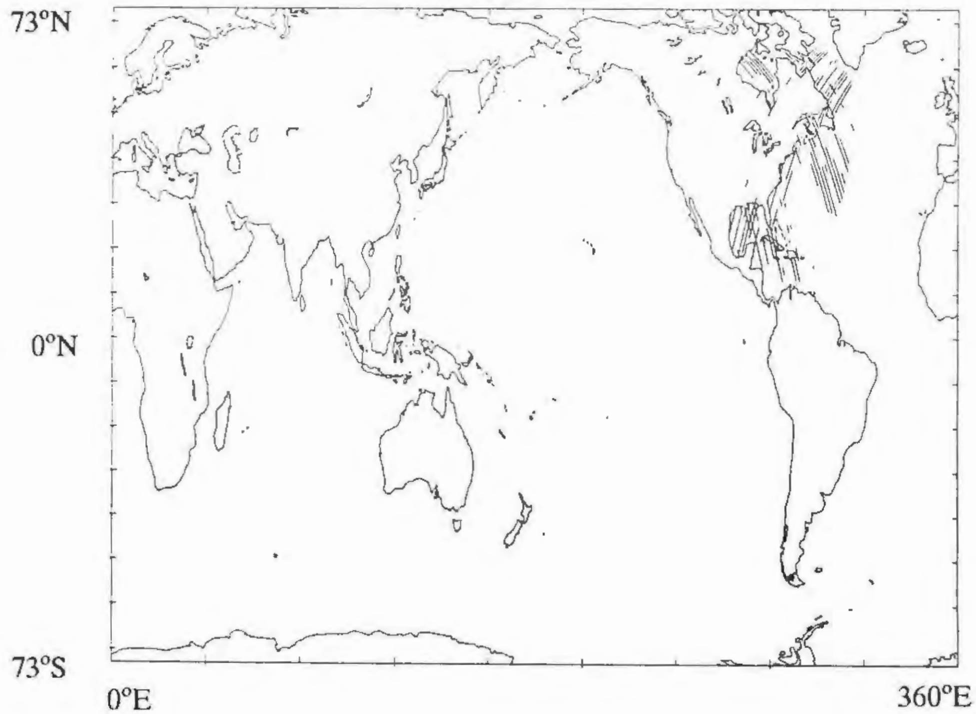
1989



ERM Cycle 63

Days 270-276

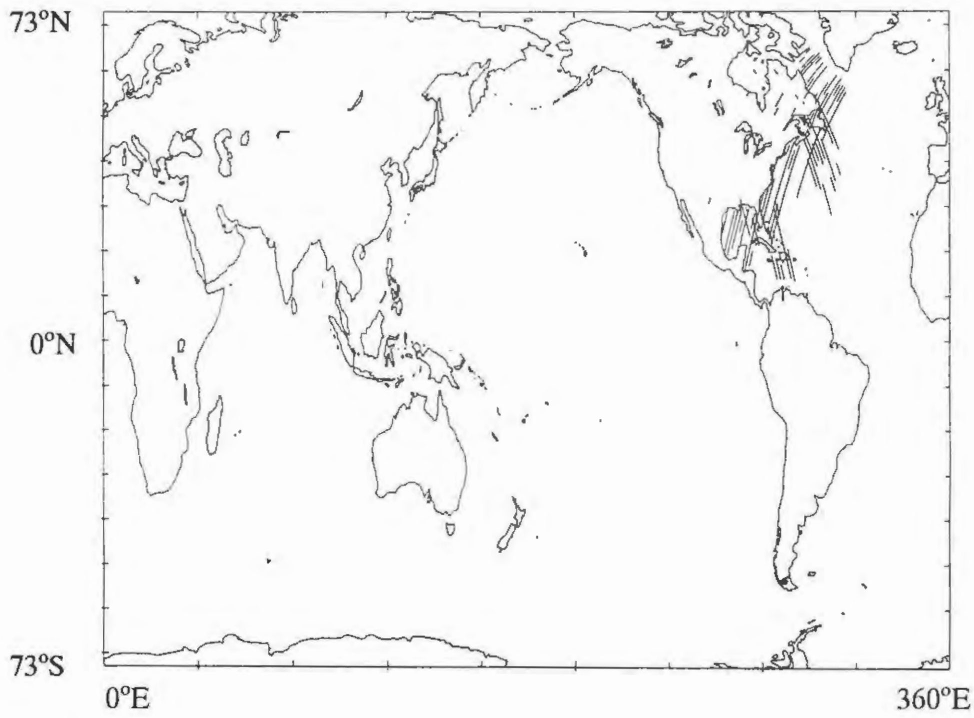
1989



ERM Cycle 65

Days 304-320

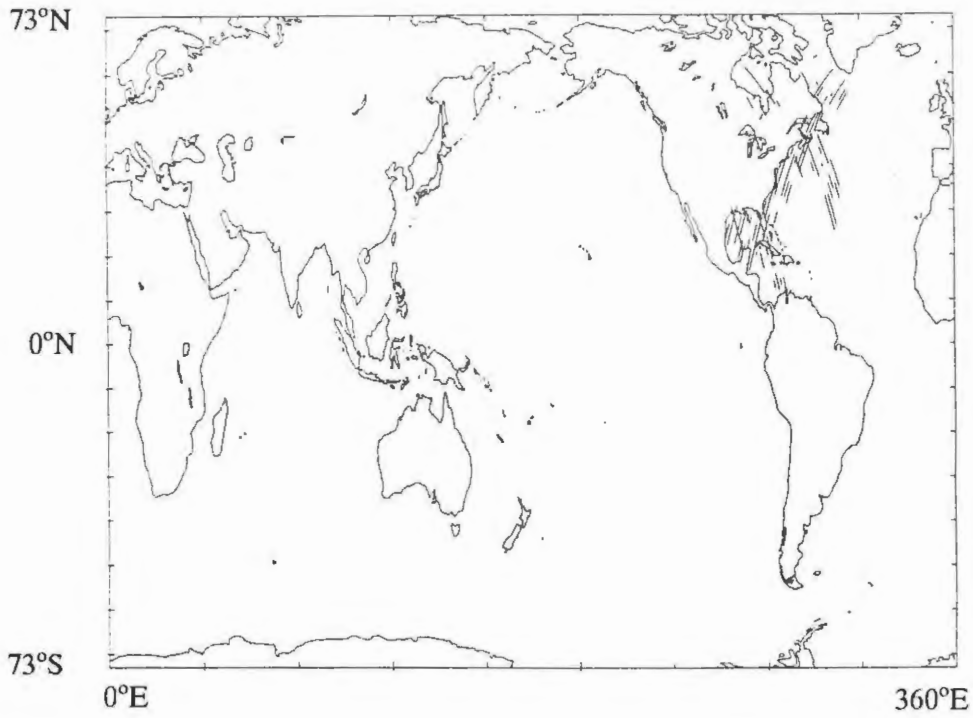
1989



ERM Cycle 66

Days 321-337

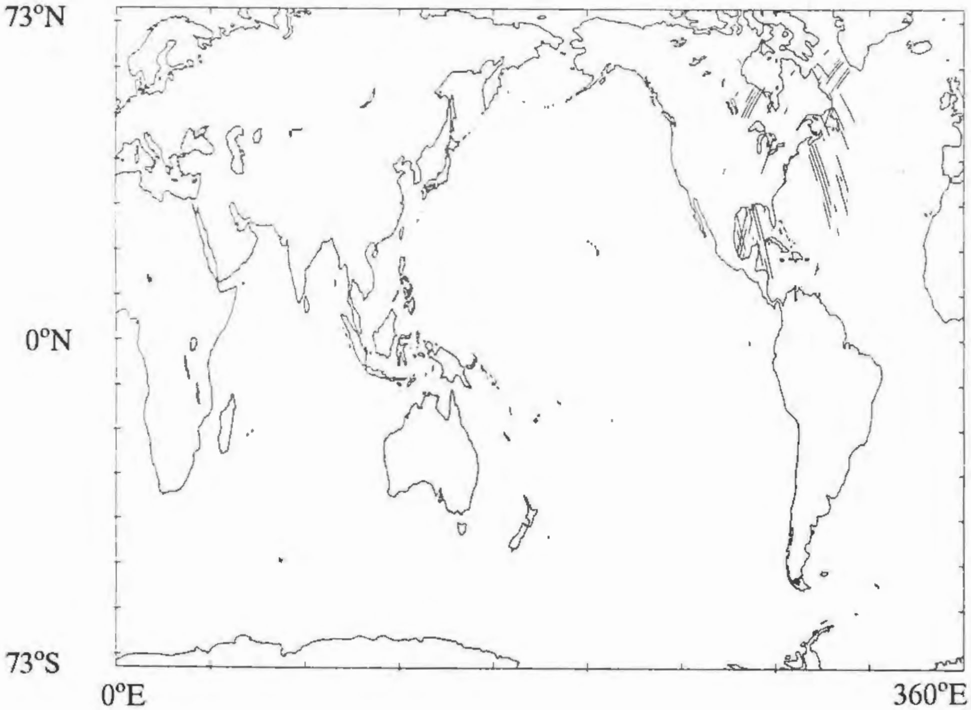
1989



ERM Cycle 67

Days 338-354

1989



ERM Cycle 68

Days 355-365

1989

NODC Environmental Information Bulletin No. 92-1

NODC on CD-ROM

Geosat Altimeter Data (T2 GDRs) *from the Exact Repeat Mission*

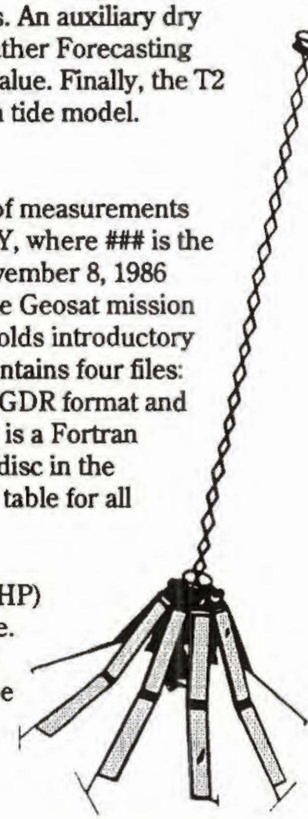
The National Oceanographic Data Center (NODC) and the National Ocean Service (NOS) are pleased to announce the release of a set of six CD-ROMs containing improved geophysical data records (GDRs) from the Geosat altimeter Exact Repeat Mission (ERM), November 1986 to December 1989. The CD-ROMs may be ordered individually or as a complete set. Each order will be accompanied by a copy of the new GDR user handbook.

Data Processing

The new Geosat GDRs have been prepared by the NOAA/NOS Satellite and Ocean Dynamics Branch. The previous versions were based on operational satellite orbits computed by the Naval Astronautics Group (NAG) and are referred to as the "NAG GDRs". A new satellite ephemeris, more precise by an order of magnitude, has since been computed by NASA's Goddard Space Flight Center. These new orbits have been incorporated in the new "T2 GDRs" (so called because the orbits are based on the GEM-T2 gravity model). In addition, the T2 GDRs contain other new fields which significantly increase the overall accuracy of the Geosat data. The most important of these is the wet troposphere correction which has been derived from satellite sensors operating during the Geosat mission. Through July 1987 water vapor was retrieved from the Tiros operational vertical sounder and thereafter from the special sensor microwave imager. These new water vapor corrections represent a vast improvement over the values provided in the NAG GDRs. An auxiliary dry troposphere correction based on the European Center for Medium-Range Weather Forecasting model is also provided in the new GDRs, enabling substitution for the FNOC value. Finally, the T2 GDRs incorporate a more accurate geoid model and modifications to the ocean tide model.

CD-ROM Contents

The Geosat T2 data on these CD-ROMs are stored in files containing one day of measurements each. The naming convention used for the individual data files is: DAY_###.YY, where ### is the Julian day number and YY is the year. Disc 1 of the set contains data from November 8, 1986 through April 9, 1987. The other CD-ROMs cover succeeding time spans of the Geosat mission through December 30, 1989. In addition to the data files, each CD-ROM also holds introductory files that provide information for working with the Geosat GDRs. Each disc contains four files: File 1 is a READ.ME documentation file; File 2 is a tabular summary of the T2 GDR format and content; File 3 is the equator crossing table for the data on that disc; and File 4 is a Fortran program that converts the data from Hewlet-Packard to VAX format. The final disc in the series, Disc 6, also contains two additional files: File 5 is the equator crossing table for all six discs, and File 6 is a table of the T2 GDR orbit epochs.



Data files on these CD-ROMs are in exactly the same binary Hewlet Packard (HP) format as the original Geosat GDRs distributed by the NODC on magnetic tape. The only difference is the storage/transfer medium. Any programs that were developed by Geosat data users to operate on the HP formatted tapes should be able to read and process data directly from the CD-ROMs. The files can be manipulated using standard MS-DOS commands, transferred over a network to a host computer, or accessed directly on CD-ROM.

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

<u>*March 1992*</u>

● ORDER FORM ● ORDER FORM ● ORDER FORM ●

GEOSAT ALTIMETER DATA (T2 GDRS) FROM THE EXACT REPEAT MISSION

DATA SELECTION:

☐ Please send me the complete set of six CD-ROMs containing Geosat Altimeter Data (T2 GDRs) from the Exact Repeat Mission. **Cost: $86*** ***($11 per disc, plus $20 order processing/handling charge)***

☐ Please send me the following selected CD-ROMs containing Geosat Altimeter Data (T2 GDRs) from the Exact Repeat Mission (check circles to specify the discs you wish to order):

	Julian Days	Dates
Disc 1 ○	Day 312 - 1986/Day 099 - 1987	November 8, 1986 - April 9, 1987
Disc 2 ○	Day 100 - 1987/Day 263 - 1987	April 10, 1987 - September 20, 1987
Disc 3 ○	Day 264 - 1987/Day 067 - 1988	September 21, 1987 - March 7, 1988
Disc 4 ○	Day 068 - 1988/Day 247 - 1988	March 8, 1988 - September 3, 1988
Disc 5 ○	Day 248 - 1988/Day 065 - 1989	September 4, 1988 - March 6, 1989
Disc 6 ○	Day 066 - 1989/Day 364 - 1989	March 7, 1989 - December 30, 1989

Cost: Number of discs X $11* per disc = $ ______

Plus order processing/handling = $ 20.00

TOTAL $ ______

(Note: *The data are stored in binary Hewlett-Packard format, but each disc contains a software module that allows the data to be converted to binary VAX format.)*

PAYMENT BY:

☐ Check or money order (in U.S. dollars, drawn on a bank in the United States, and made 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 ______________________

MAILING ADDRESS:

Name ______________________

Title/Department ______________________

Organization ______________________

Street Address ______________________

City ______________ State ________ Zip ______________

Country ______________________

Telephone No. (with area code) ______________________

*(*Prices quoted in this order form are for Fiscal Year 1992; they are in effect until September 30, 1992. For prices after that date, please contact the NODC.)*

TO ORDER

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

BY TELEPHONE: (202) 606-4549 BY FAX: (202) 606-4586