NOAA Manual NOS NGS 6

Geosat Altimeter Crossover Difference Handbook

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

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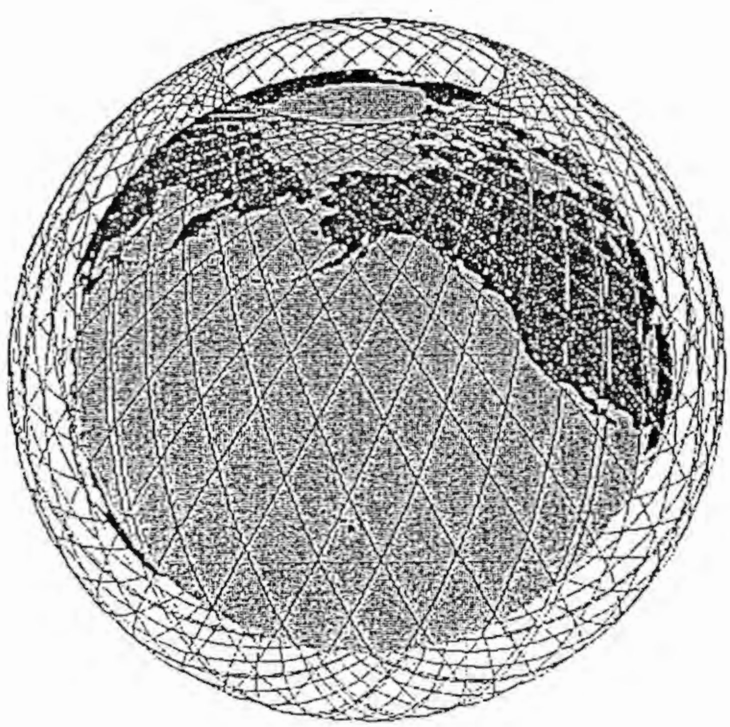

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Service
Rockville, MD

Availability

The Geosat crossover difference data set, together with the handbook, is 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) 673-5549
Electronic Mail: OMNET/MAIL mailbox NODC.WDCA

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

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

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

Cover Illustration - Three days of the Geosat trajectory.

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Contents

Abstract

The first 18 months of the Geosat altimeter sea level data (April 1985 to September 1986) are secret but can be declassified when converted to crossover differences. We have constructed a global set of Geosat crossover differences consisting of approximately 44 million values. These data include not just the initial 18-month geodetic mission but also the first year of the subsequent exact repeat mission. This enables computation of continuous, 2.5-year sea level time series spanning the two missions. In a similar fashion, this will allow the 1985-86 Geosat records to be referenced to future altimeter observations for determination of interdecadal sea level changes.

I. Introduction

The U.S. Navy Geosat altimeter mission lasted for nearly 5 years, from April 1985 to January 1990. Geophysical data records (GDRs) from the final 3 years, when the satellite was performing the exact repeat mission (ERM), were produced by NOAA's National Ocean Service (*Cheney et al.* 1987) and have been widely distributed. The intense interest in these data is indicated by the many articles published in the March and October 1990 issues of the *Journal of Geophysical Research (Oceans)* dedicated to the Geosat mission.

In contrast, GDRs from Geosat's first 18 months (April 1985 to September 1986), known as the geodetic mission (GM), are classified because of military applications related to knowledge of the marine geoid. Only the altimetric heights are considered secret, however, and unclassified subsets of these data can be released. For example, global Geosat wind speed and wave height data from the GM are available through NOAA (*Dobson et al.* 1988), and the waveform data records for the entire GM are also available.

Another unclassified data type is the crossover difference. A crossover is defined as the intersection of the satellite ground track with itself. At this location, the two crossing passes (one ascending and one descending) provide independent sea level measurements at the same place but at different times. The difference of these two sea level measurements (a crossover difference) is not considered classified because the geopotential component of sea level is the same at the intersection of the two tracks and thus cancels. Crossover differences contain information about uncertainties in the satellite ephemeris (*Marsh and Williamson* 1980) and therefore enable correction of radial orbit error (*Sandwell et al.* 1986, *Cheney et al.* 1989). Orbit-corrected crossover differences form the basis for studies of sea level variability, both in a statistical sense (*Cheney and Marsh* 1981) and for computation of sea level time series (*Fu and Chelton* 1985, *Miller et al.* 1986, *Cheney et al.* 1986, *Tai et al.* 1989). Tide model studies represent another type of crossover difference application (*Schwiderski* 1990).

This report documents the Geosat crossover difference records or "XDRs". Although only the 18-month GM data are classified, we have constructed XDRs for the first 2.5 years of the Geosat mission, that is, data from the GM plus the first year of the ERM. This was done to minimize the effect of the 5-week data gap (October 1 to November 8, 1986) between the two missions when the altimeter was off during orbit maneuvers. By computing crossovers for the entire 2.5-year period, continuous sea level time series can be derived. For example, figure 1 shows a small set of crossovers in the western Pacific near the island of Ponape. The time

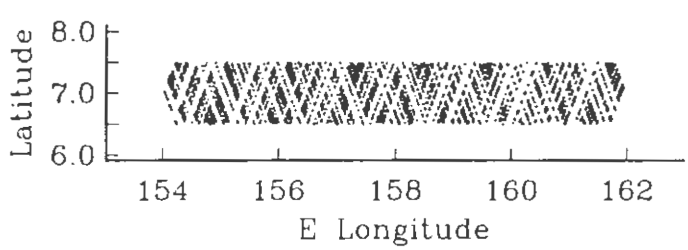

Figure 1. Distribution of Geosat crossovers in the 8° by 1° region centered on Ponape.

series solution derived from this 8° by 1° network of crossovers is shown in figure 2. The October-November 1986 gap may be treated in the same way as any other data gap in the record. Having derived the raw time series (one measurement of sea level for each Geosat pass traversing the study area), one may either interpolate across the 5-week gap as we have done, or delete this period from the analysis. Regardless, because the XDR contains both ERM and GM passes, a continuous time series from 1985 to 1987 is obtained. An analogy would be a multiyear tide gauge record in which a few weeks of observations were missing. In fact, as shown in figure 3, Geosat time series typically agree with island tide gauges at the level of a few centimeters.

It is important to understand that sea level time series and other oceanographic information can only be derived from XDRs which have been adjusted to remove radial orbit error (approximately 1 m amplitude). The NOAA XDR tapes contain all information necessary to perform such adjustments, but no orbit corrections are provided. Removal of orbit error is essentially a filtering problem, and different oceanographic applications require different approaches. For a summary of various methods for dealing with orbit error and their effect on the ocean signal, see *Tai* (1991).

Crossover differences will continue to play an important role in future altimeter missions, even though most will have exact-repeat ground tracks. The reason is that crossovers provide a direct means of connecting data sets. For example, altimeter data from ERS-1 and Topex/Poseidon in the 1990's can be crossed with Geosat data or even Seasat data to observe interdecadal sea level changes.

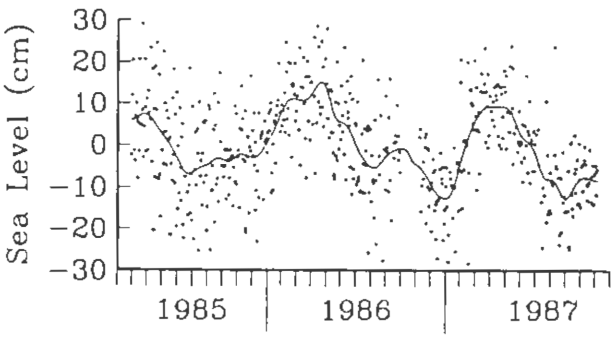

Figure 2. Sea level as a function of time derived from Geosat crossover differences in figure 1 after applying orbit and environmental corrections. Dots represent sea heights computed from individual passes (approximately two passes every 3 days). The smooth curve is computed using objective analysis where a 30-day decorrelation is assumed.

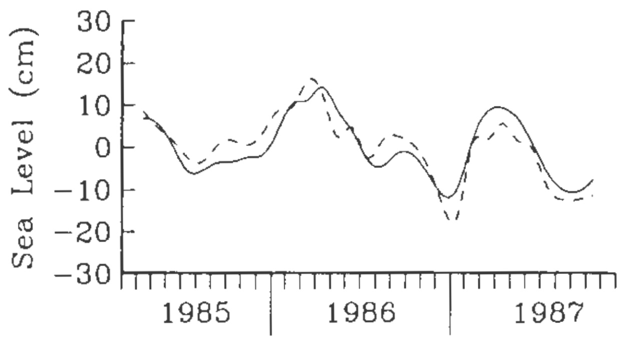

Figure 3. Comparison of the Geosat record (solid) with the Ponape tide gauge record (dashed). Monthly values were extracted from charts published by the University of Hawaii, and the filtered Geosat record was averaged over the same 1-month intervals. Each curve was adjusted to have zero mean over the entire 2.5-year period. The comparison yields 3.7 cm rms difference and 0.88 correlation (from Cheney and Miller 1990).

II. The Classified Geosat GDRs

Crossovers involving data from the first 2.5 years of the Geosat mission are based on classified GDRs which we produced in a secure computer facility at the Johns Hopkins University Applied Physics Laboratory. These are similar in content to the unclassified ERM GDRs, and most of the relevant information is therefore contained in the GDR user handbook (*Cheney et al.* 1987). Figure 4 shows the number of GDRs per day for the first 2.5 years of the mission. Approximately 55,000 1-sec records were collected daily.

Ephemeris computations for the classified GDRs 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 for the 2.5-year period was generated by overlapping consecutive spans by two revolutions and then using a cosine smoother to eliminate discontinuities (*West* 1986). As documented by *Cheney and Douglas* (1988), use of a single gravity model for orbit determination is absolutely essential to avoid fictitious height changes due to geographically correlated orbit error.

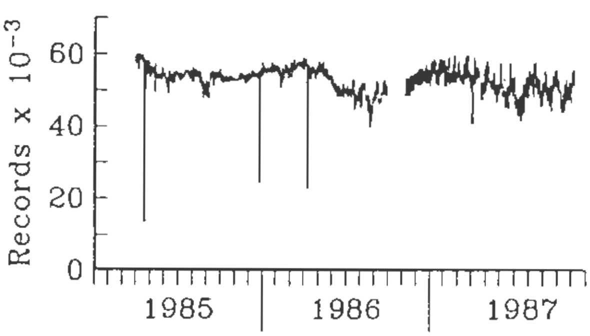

Figure 4. Number of 1-sec GDRs for each day of the Geosat mission from April 1, 1985 to November 8, 1987.

Geosat's Doppler beacon was tracked by the network of approximately 40 stations operated by the Defense Mapping Agency. The excellent global coverage provided by this network together with the relatively low atmospheric drag during 1985-87 resulted in an ephemeris with a precision of approximately 60 cm. The precision varied with time as shown in figure 5 where we have plotted the rms crossover difference for global Geosat data sets. Values range from 60 to 110 cm, implying radial orbit precision of 40 to 80 cm (after dividing by the square root of 2, see *Marsh and Williamson* 1980).

During the GM the ground track never repeated exactly, but near-repeats occurred at 23-day intervals. Ground tracks showing the global coverage for each of these intervals are provided in the appendix. Ground tracks for the first year of the ERM can be found in *Cheney et al.* (1988).

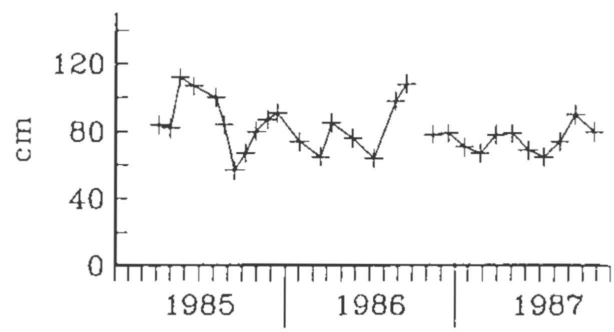

Figure 5. Global rms crossover difference at monthly intervals during the first 2.5 years of the mission. Corrections were applied for tides, FNOC troposphere, and ionosphere, but no adjustment was made for orbit error. Each value was determined from 10 days of Geosat data and is based on approximately 7,000 crossovers over the global oceans.

III. Generation of the XDRs

A new algorithm for generating crossover difference data sets was developed to enable determination of all possible crossovers from the large amount of Geosat data (3.6 Gigabytes) in the 2.5-year Geosat period. Our approach separated the process into two steps:

(a) *Determination of crossover locations and times*

Because the satellite path changes in a smooth, predictable way, it is sufficient to store its position (in three dimensions) at 1-minute intervals of time. The satellite ephemeris is therefore a small data set (25 megabytes for 2.5 years), yet it contains sufficient information to describe the ground track with very high precision when interpolated using a ninth-order polynomial. In the first step of computing crossover differences, we access the ephemeris to create a file of precise crossover locations and times. Crossings are excluded over land and selected inland lakes and seas using a 1-degree mask. Each crossover consists of two direct access records: one for the ascending pass and one for the descending pass. Because adjoining records may have widely differing times (up to 2.5 years apart in this case) the ascending and descending XDRs are each linked chronologically so that they can be read as a time-ordered list.

(b) *Incorporation of altimeter heights*

In the second step, altimeter data are interpolated at the precise times given in the XDR to determine sea level and environmental corrections at the crossover locations. Because both XDRs and altimeter profiles are accessed chronologically, there is no need to have all altimeter data simultaneously online, and very large crossover data sets can be constructed.

The interpolation of sea level was done in the following way. First, the 10/sec data from the GDR were compressed to 2/sec through a process involving quadratic fits to 2-sec spans of data. The resulting 2/sec values were put into a data management system to enable rapid access based on time and/or Equator crossing longitude. These compressed GDRs were then used to determine sea level at the crossover times by quadratic fits to seven heights, all of which must have occurred within a 4-sec span centered at the crossover. Data points with the largest residuals were discarded until the solution converged to within 2 cm. A minimum of five heights was required; otherwise the crossover height was flagged by assigning it a value of 2,147,483,646 ($2^{31} - 2$). Correction fields (tides, troposphere, ionosphere) were incorporated in the XDR using simple linear interpolation over 4 sec because of the relatively coarse spatial resolution of these fields.

Once all ascending and descending crossover records were evaluated, sea level differences were formed, thereby removing the geoid. The convention used was

$$\Delta = \text{Ascending} - \text{Descending}$$

Differences of the correction fields were also computed. Other fields used in quality control (e.g., flags, spacecraft attitude) were carried separately for ascending and descending passes.

IV. XDR Content and Format

Table 1 summarizes the fields contained in the XDRs. Short explanations and applications notes are provided in table 2. The GDR user handbook should be consulted for more detailed information. Inclusion of environmental correction differences enables replacement of these fields by improved versions if desired. However, because the satellite ephemeris is classified, orbit differences could not be provided, and it will not be possible to replace the satellite orbit.

In cases when no data were available for a particular field, the value was flagged by inserting a value of 32,767 (2^{15} - 1) for a 2-byte field and 2,147,483,646 for a 4-byte field. This occurred when there were gaps in the data or when noisy height data resulted in a lack of convergence in the sea level interpolation routine. However, note that the XDR contains a record for every possible crossing over the ocean, regardless of the altimeter data content. For example, if neither ascending nor descending height was available at the crossover, the XDR record will still contain position and the two times with all other fields flagged. If only the ascending height was available, the XDR record will contain position, times, and all parameters pertaining to the ascending pass; all difference fields and descending parameters will be flagged. This was done to provide as complete a record as possible for the Geosat crossovers.

The data are binary (no format) and should be readable on any two's complement computer because all data are stored as integers. On a two's complement machine, an integer is converted to its negative by flipping all its bits and adding 1. Thus, for 2-byte integers of magnitude 9, the bits would be:

0 000 000 000 001 001 for +9

1 111 111 111 110 111 for -9.

A one's complement computer just flips all the bits, resulting in a negative zero which is generally regarded as undesirable. Additionally, a Fortran sequential file (binary or formatted) has either 2- or 4-byte record lengths before and after each record. Thus each 72-byte record from the tape occupies 76 or 80 bytes when an appropriate utility transfers the data to such a disc file. On some systems, a utility may not add the record lengths, e.g. *dd* under Unix. In that case a Fortran program must access the data as a direct access file of record length 72 bytes.

Table 1. XDR Contents

Item	*Parameter*	*Units*	*Bytes*
1	Latitude	microdeg	4
2	Longitude	microdeg	4
3	UTC (A)	sec	4
4	UTC (A) cont'd	microsec	4
5	UTC (D)	sec	4
6	UTC (D) cont'd	microsec	4
7	Spare		2
8	Spare		2
9	Δ H	mm	4
10	Δ TID	mm	4
11	Δ WET (FNOC)	mm	4
12	Δ WET (SMMR)	mm	4
13	Δ DRY (FNOC)	mm	4
14	Δ IONO	mm	4
15	σ_H (A)	mm	2
16	σ_H (D)	mm	2
17	SWH (A)	cm	2
18	SWH (D)	cm	2
19	σ_0 (A)	0.01 db	2
20	σ_0 (D)	0.01 db	2
21	Flag (A)		2
22	Flag (D)		2
23	Attitude (A)	0.01 deg	2
24	Attitude (D)	0.01 deg	2
		Total	72

Table 2. Definitions

Item	*Parameter*	*Definition*
1	Latitude	North latitude (negative for south) of the crossover point.
2	Longitude	East longitude of the crossover.
3-6	UTC	Universal Time Coordinated in sec/microsec. (A) = ascending pass (D) = descending pass UTC = 0 refers to January 1, 1985, 0 hours, 0 min, 0 sec.
7-8	Spares	These two fields were intended to be pass identification numbers. The algorithm for computing these from UTC was later determined to be inaccurate, and many of the pass numbers are incorrect. Although items 7 and 8 contain values, they should be ignored.
9	Δ H	Uncorrected crossover difference value, defined as: $\Delta H = H(A) - H(D)$ To apply corrections: $\Delta H (corr.) = \Delta H - \Delta TID - \Delta DRY - \Delta WET - \Delta IONO - \Delta INBAR$ All fields on the right of the equation are provided with the exception of Δ INBAR (the sea level change due to the inverted barometer effect). This quantity must be computed as follows: $\Delta INBAR = \Delta DRY (4.3689)/(1+0.0026 \cos 2\phi)$ where ϕ = latitude in degrees.
10	Δ TID	Difference of the combined solid and ocean tide.
11	Δ WET (FNOC)	Difference of the wet troposphere correction using the Fleet Numerical Oceanographic Center (FNOC) model.

Table 2. Definitions (continued)

Item	*Parameter*	*Definition*
12	Δ WET (SMMR)	Difference of the wet troposphere correction from 1979-81 SMMR data. This is an auxiliary value to be used in lieu of Δ WET (FNOC).
13	Δ DRY	Difference of the dry troposphere correction using the FNOC model.
14	Δ IONO	Difference of the ionospheric correction.
15-16	σ_H	Standard deviation from a linear fit to the 10/sec sea heights used in computing the 1/sec values of H provided in the GDR.
17-18	SWH	Significant wave height or $H_{1/3}$.
19-20	σ_0	Backscatter coefficient (sigma naught).
21-22	Flag	Flag bits 0-15, right to left

0 = 1	if over water
1 = 1	if over water > 2000 m depth
2 = 1	if either dh(SWH/ATT) or dh(FM) out of range
3 = 1	if any of the 10/sec heights out of range
4 = 1	if VATT is extrapolated
5 = 1	if VATT is estimated
6 = 1	if VATT estimate used < 60 raw samples
7 = 0	not used
8	checksum (NOAA use only)
9	checksum
10	checksum
11	checksum
12 = 1	if FNOC interp > 12 hrs
13 = 1	if solar flux value out of range for ionos model
14 = 0	not used
15 = 0	not used

23-24	Attitude	Spacecraft attitude

V. Reading the XDR Files

The following Fortran program demonstrates how the data can be read from a binary sequential file and listed on an HP 1000 computer:

```
      PROGRAM READ
      INTEGER*2 N,LUF,LU,IOS,J,I
      INTEGER*4 Q
      CHARACTER*63 OFILE
C
      DIMENSION Q(18),N(36)
      EQUIVALENCE (Q(1),N(1))
C
    1 FORMAT (' Enter XDR file name:')
    2 FORMAT (A)
    3 FORMAT ('  Record',I4,':',6I11,2I7 /12X,6I11  /12X,10I7)
C
   90 FORMAT (/' I/O error',I6,'!, on ',A)
C
      LUF= 58
      LU= 1
C
      WRITE (LU,1)
      READ (LU,2) OFILE
C
      OPEN (LUF,FILE=OFILE,IOSTAT=IOS,ERR=9000,STATUS='OLD')
C
C  read and list the first 10 records:
C
      DO J=1,10
        READ (LUF,IOSTAT=IOS,ERR=9000) Q
        WRITE (6,3) J, (Q(I),I=1,6), N(13),N(14), (Q(I),I=8,13),
     1  (N(I),I=27,36)
      ENDDO
C
      CLOSE     (LUF,IOSTAT=IOS,ERR=9000,STATUS='KEEP')
      STOP
C
 9000 CONTINUE
      WRITE (LU,90) IOS,OFILE
      STOP
      END
```

VI. Regional Data Sets

The XDRs were generated in 18 ocean regions (fig. 6). Crossovers over land and ice were excluded because retracking of the altimeter data would have been required to obtain reliable values (*Martin et al.* 1983). Most ocean regions contain altimeter arcs of at least 3,000 km, sufficiently long for mesoscale variability studies. In order to construct longer arcs, data from different regions will have to be combined. Each area includes between 1.4 and 3.1 million crossover locations, and the data for each region occupy two 6250-bpi density tapes.

The exact number of crossovers in each region is provided in table 3 together with other statistics. Although the complete set of XDRs consists of approximately 65 million crossover locations, only 44 million crossover differences could be formed because of data gaps. For example, table 3 shows that in the northwest Pacific (area 1), 14 percent of the ascending crossover heights and 33 percent of the descending heights could not be computed, resulting in 40 percent of the crossover differences being lost. This is consistent with the ground track maps which show persistent gaps in many mid- and high-latitude areas, especially those in which the satellite passes from land (or ice) to ocean. In contrast, the tropical regions had relatively good coverage. For example, in area 9 (tropical Pacific), 88 percent of all possible crossovers could be determined.

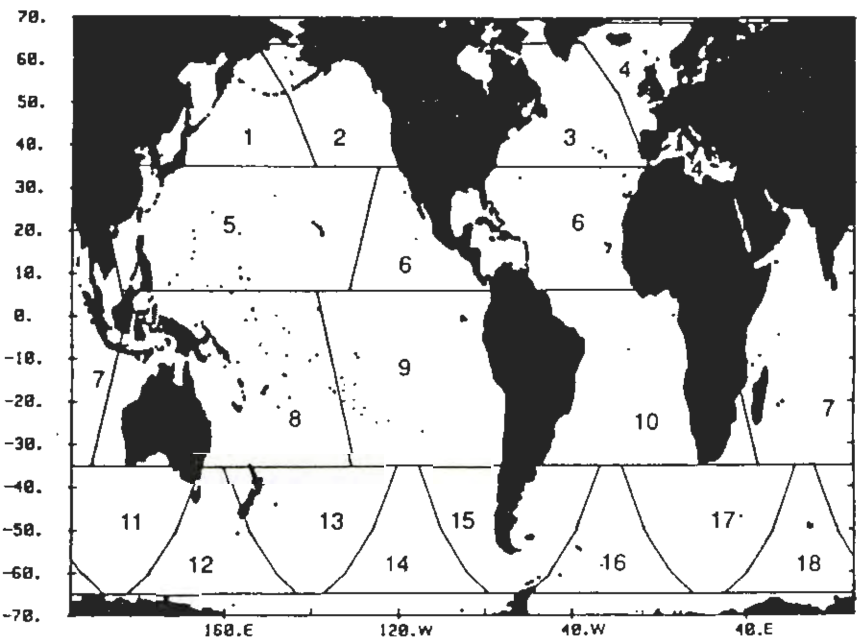

Figure 6. Regions in which Geosat crossovers were computed. Because of the extremely large number of global crossovers (approximately 65 million over the oceans), computations were performed separately for 18 areas. Each area contains approximately 3 million crossovers. The land mask shown excluded crossovers in some inland seas and lakes.

Table 3. XDR Statistics

Area	Total XDRs	% Missing: H_A	H_D	Usable XDRs	Mean $\Delta H(cm)$	$\sigma_{\Delta H}$ (cm)
1	2,831,104	14	33	1,686,897	-35	100
2	2,577,423	13	39	1,430,720	-19	127
3	3,768,889	23	40	1,936,457	-39	103
4	3,783,108	27	33	1,986,905	- 4	106
5	3,654,819	7	20	2,764,442	-17	91
6	3,461,209	8	14	2,794,629	-16	88
7	3,632,046	11	8	2,993,383	- 6	93
8	3,689,076	12	10	2,945,467	-12	90
9	3,496,910	8	5	3,065,717	0	89
10	2,849,011	10	5	2,452,226	-14	94
11	3,795,607	26	10	2,587,166	-48	91
12	3,906,673	22	13	2,770,111	1	90
13	3,862,675	18	6	3,025,254	24	84
14	3,805,980	19	7	2,891,061	- 3	85
15	3,857,880	24	9	2,766,078	56	100
16	3,769,983	51	37	1,388,751	17	86
17	4,123,595	14	9	2,799,082	- 5	91
18	3,683,476	42	31	1,716,867	35	88
	64,599,476			44,001,213	-85	94
	Total			*Total*	*Average*	*Average*

VII. Correction for Orbit Error

Computed satellite orbits suffer from low-frequency, large-scale, systematic error. It is well known that most of this error (the radial component) can be eliminated from crossover differences through least squares adjustment, where the error is modeled as a linear or quadratic trend over arc lengths of several thousand kilometers (*Tai* 1989). In *Milbert et al.* (1989), *Cheney et al.* (1989), and *Cheney and Miller* (1990) we document the methods used in our analyses of the 2.5-year Geosat crossover differences. A summary is provided here.

Error in the radial (altitude) component of a satellite arises largely from two sources. These are errors in the initial conditions (usually called orbital elements) and errors arising from uncertainty of the geopotential. The latter uncertainty is one of many causes of the former, and also produces an error in the radial component of position that is geographically correlated, that is, repeats at the same location. It is evident that the geographically correlated signal plays no role whatever in determination of oceanic variability, since it is the same on both passes at a crossover point and vanishes in the difference. However, the initial condition error produces a spatially very long wavelength signal that is partially observable in crossover differences and must be removed (high pass filtered) before sea level variations can be computed from crossover differences.

For a planet covered uniformly by water, removal of radial orbit error and other long wavelength signals would require only simple high pass filtering of the altimeter data. The real Earth and Geosat present a much more complicated filtering problem because of data gaps caused by land. For our work we have taken a regional approach in order to minimize problems associated with these gaps.

The orbit error model used for our investigations is a low degree polynomial in time, usually a linear or quadratic function of the form

$$O = a + b\,(t - t_0) + c\,(t - t_0)^2 \qquad (1)$$

where O is orbit error, a, b, and c are unknown coefficients unique to each satellite pass of data in the region, t is time along the satellite trajectory, and t_0 is the Equator crossing time for the pass under consideration. Altimeter arc lengths of 10,000 km are typically used. For a large crossover data set, it is impractical and unnecessary to solve simultaneously for the polynomial coefficients in all of the passes of data available. Instead we divide the orbit correction process into two steps followed by a third in which sea level time series are computed:

(a) Constructing a precise reference surface

The first step is to form a temporally contiguous, spatially uniform reference grid of passes, such as a regional subset formed from any of the 23-day sets of data illustrated in the appendix. For example, *Cheney et al.* (1989) constructed a 23-day reference surface spanning the Pacific Ocean and extending from 40°N to 40°S. This grid contained 417 passes that intersected in 8,973 places, and the unadjusted rms crossover difference value was about 1 m. Solving simultaneously by least squares for the three coefficients in equation (1) for each pass reduced the adjusted crossover rms to about 8 cm, a level consistent with real sea level variability together with a few centimeters of residual error.

Several points must be emphasized here. The reference surface possesses an overall bias due to datum defects (singularities), since only crossovers are used in the orbit error model. Therefore, only relative orbit error is recovered. One pass must be held fixed (a, b, c unadjusted) and another will have tilt and curvature fixed. Further, any ocean signal appearing as a tilt or quadratic curve along the orbital ground track will be indistinguishable from orbit error and thus absorbed into the coefficients. The orbit-corrected sea level variations are not satisfactory for monitoring the meridional variation of the entire Pacific Ocean, for example.

(b) Adjustment of all passes with respect to the reference surface

In the second step, orbit error is removed from all later (non-reference) passes in the data set. Each pass is individually adjusted into the precise grid based on its crossings with the reference passes. Most of the passes in the equatorial Pacific intersect the grid described above in about 60 places, more than enough to determine the coefficients for each pass. Since the equation for each pass contains only two or three unknowns and a relatively small number of crossover differences, the adjustment proceeds rapidly.

(c) Generation of sea level time series

The third and final step in the process is to compute sea level time series from orbit-adjusted crossovers in relatively small regions. These data contain sea level variability not absorbed into the polynomial coefficients. To analyze the tremendous number of crossovers that exist in an ocean basin, the region is divided into small "boxes" whose size and shape are determined by the physics of the region and the geometry of the passes of data. As an example, to study low-frequency, long-wavelength, sea level variability associated with El Nino in the equatorial Pacific, *Cheney et al.* (1989) chose 1° latitude by 8° longitude geographic polygons such as shown previously in figure 1. In the 2.5-year period covered by the Geosat XDRs there are about 400 passes and 3,500 crossovers in each of these polygons. Hexagonal regions (truncated diamond-shapes) were chosen because they produce a more uniform sampling of crossover time differences than rectangles. The elongated shape of the regions also gives a dense temporal sample of variability, 2 observations every 3 days.

It is important to recognize that a given pass traversing the polygon in figure 1 does not intersect every other pass in the polygon, but together the passes form a network. After assuming an arbitrary height (say zero) for the mean sea surface height of the polygon, the relative height of each pass in the polygon can be estimated based on the differences of height at the crossovers. In this way, the 3,500 crossovers in figure 1 are used to compute the individual, average heights in the polygon for the 400 passes that traversed it. Again, these are not absolute sea surface heights, since there is only relative information in crossover data.

The crossover difference model is written

$$L = D_j - D_i \tag{2}$$

where D_i and D_j denote estimates of sea level for passes at time t_i and t_j. This forms an adjustment model

$$l = Ax + n \tag{3}$$

where

- l is a vector of crossover differences
- x is a vector of sea height parameters
- A is a matrix relating l and x
- n is the crossover difference noise vector.

In addition we impose a constraint

$$D_k = 0 \quad (4)$$

for all k time epochs, which is equivalent to requiring that the mean value of sea heights in the polygon be equal to zero. We choose a datum with the mean removed for convenience in subsequent interpolation.

In summary, adjustments performed in each of the three steps outlined above produce a spatial filter. In the first two steps, variations with a meridional length scale of 10,000 km or longer are removed by absorption into the orbit error coefficients. Then variations with a meridional scale of approximately 100 km (the latitudinal extent of the polygon) are treated as noise by the second adjustment. This process produces estimates of the sea surface variation denoted by the dots in figure 2. In addition to these "raw" estimates, a smoothed time series is also produced (the curve in fig. 2).

VIII. Precautions

Although analysis of the Geosat crossovers should always include correction for orbit error as outlined in the previous section, it is instructive to examine characteristics of this error in the *unadjusted* XDRs. The following analyses were performed to evaluate the effect of Geosat orbit error on determining changing thickness of the Greenland ice sheet (*Douglas et al.* 1990), but the results serve as a general warning against use of unadjusted Geosat crossover differences for any scientific purposes.

To be consistent with the Geosat analysis of Greenland ice by *Zwally et al.* (1989), we considered only the GM. For large ocean areas, the true trend of sea level computed over 18 months should be relatively small (less than 10 cm per year). As evidence of this, we note that the seasonal sea level signal is typically 5 cm in amplitude (*Levitus* 1984; *Wyrtki and Leslie* 1980) which, in a worst case, could produce an 18-month trend of only 6 cm per year. Furthermore, averaging over large ocean areas will eliminate contributions from the eddy field. The largest sea level trends would be found in the tropical Pacific Ocean, where a large-scale change of more than 10 cm per year could occur during El Nino, but the Geosat GM data represent a non-El Nino period.

We first examined a large region in the North Atlantic (50-60°N, 310-335°E) just south of Greenland which contained 156,355 Geosat GM crossover differences. This is an area of relatively low mesoscale variability; *Fu et al.* (1988) found values of less than 10 cm rms for one year of Geosat ERM data. Using the standard XDR convention

$$\Delta H = H(A) - H(D)$$

the mean crossover difference for this region is -53 cm, indicating a significant bias of the ascending passes relative to the descending passes. Standard deviation of the crossover differences is 90 cm, an indication of the radial orbit precision. (In this analysis, the following corrections were applied: TID, WET (FNOC), DRY (FNOC), IONO, INBAR, and 1 percent of SWH as a sea state bias.)

Figure 7 is a plot of the height differences as a function of the time difference. Negative time differences are a consequence of the ascending-minus-descending convention used; in terms of actual time spanned, all data occur within the same 18 months. A linear fit to these data yields a positive slope of 44 cm per year. Clearly this trend is not oceanographic in nature, but rather is an artifact related to time-variable orbit error.

A series of diagnostic tests showed the trend to be very well determined for this North Atlantic region. First, we obtained exactly the same 44 cm per year value when all environmental corrections were removed from the crossovers. Next, we divided the data into two equal groups based on the sign of the time difference: those with negative time differences gave 40 cm per year, while those with positive ones yielded 43 cm per year. Finally, we separated the crossovers into quadrants to examine regional dependence of the trend. The northwest and northeast quadrants gave 49 and 50 cm per year, respectively, while the southwest and southeast regions yielded 44 and 38 cm per year. This apparent dependence on latitude was verified by performing similar calculations in other ocean regions worldwide. Southwest of New Zealand, antipodal to the North Atlantic, we obtained a trend with the same magnitude (39 cm per year), but opposite sign. Near-zero values were found at the Equator, while trends as large as 55 cm per year were found at 69°N in the Norwegian Sea. The trend in the Geosat crossovers therefore varies approximately linearly as a function of latitude.

We conclude that the *unadjusted* Geosat XDRs are seriously contaminated by large-scale, low-frequency error of the satellite ephemeris. Although the exact cause of this trend in the ephemeris is not known, it is clear that unadjusted altimeter crossovers must not be used for determination of low-frequency trends over the ocean or ice. Pass-by-pass adjustments must be performed to derive useful information. When orbit error is properly treated, however, the Geosat crossovers can provide sea level time series that are accurate at the sub-centimeter level when averaged over large ocean areas (*Miller and Cheney* 1990).

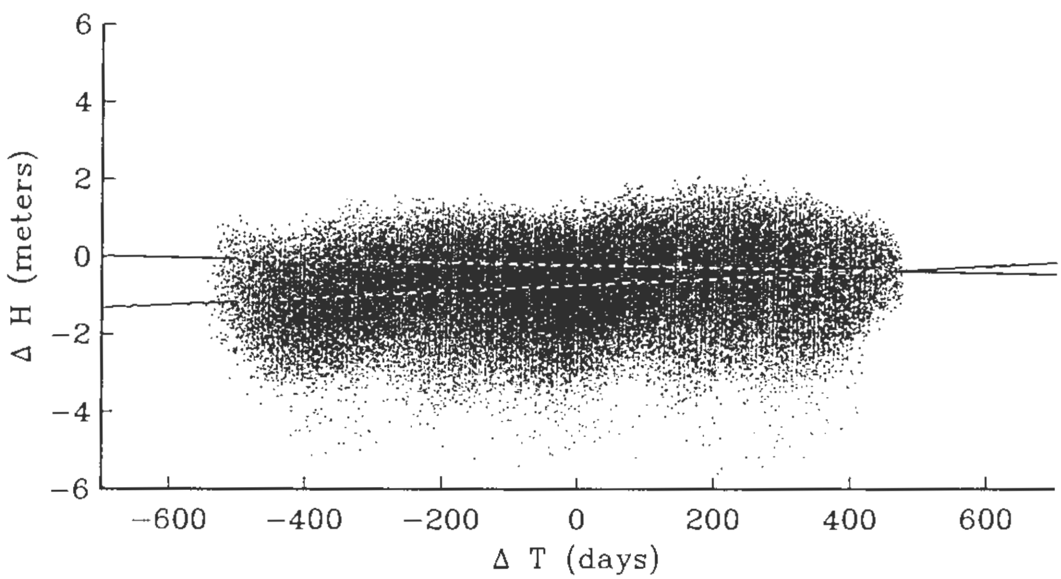

Figure 7. Geosat crossover differences in the North Atlantic south of Greenland (50-60°N, 25-50°W) plotted as a function of time differences. Corrections were applied for tides, FNOC troposphere, inverted barometer, sea state bias (1 percent of SWH), and ionosphere, but no adjustment was made for orbit error. Only data from the 18-month GM are included. (Use of the ascending-minus-descending convention results in both negative and positive time differences.) Scatter of these 156,355 values is 90 cm rms, consistent with the radial orbit error. However, the data also reveal a systematic, upward trend of 44 cm per year, also an artifact of orbit error. Such trends must be removed from the Geosat XDRs before meaningful results can be obtained.

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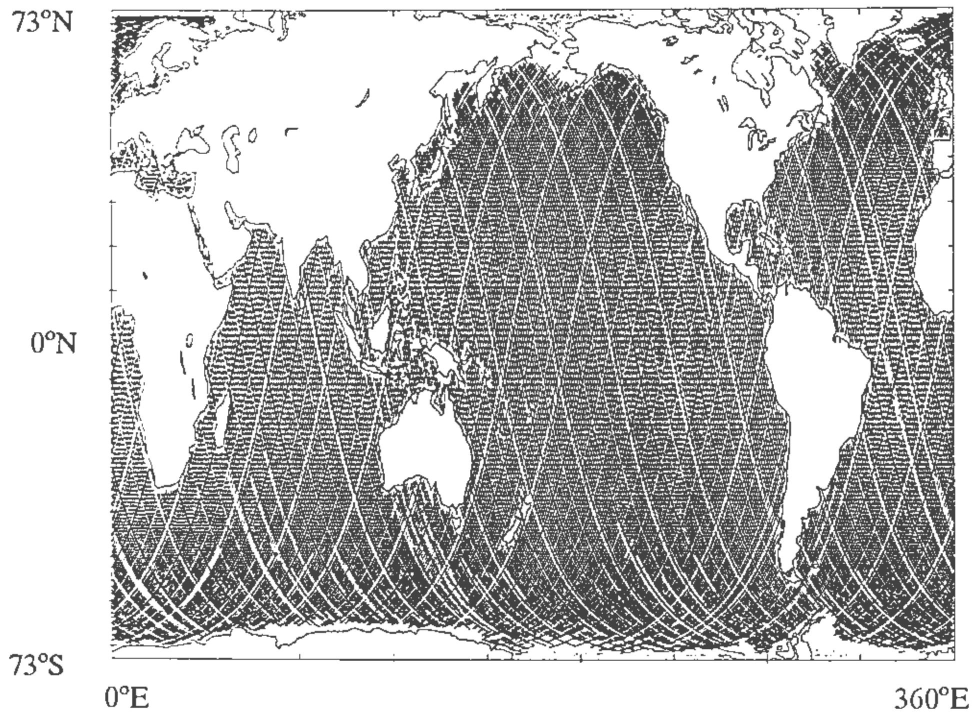
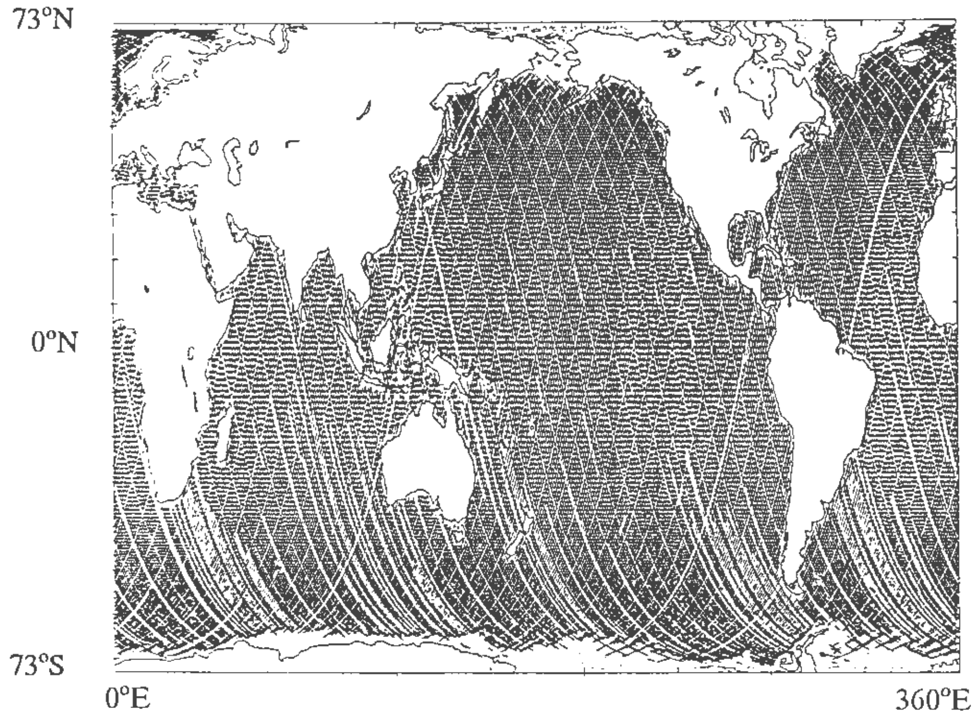


GM Cycle 1

Days 90-113

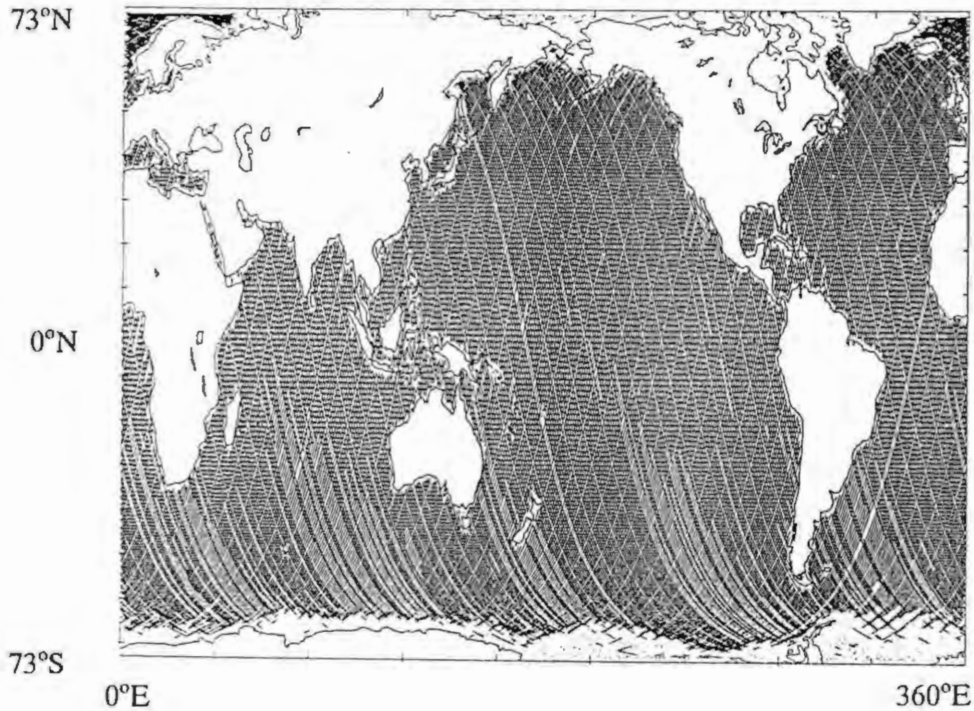
1985



GM Cycle 2

Days 114-136

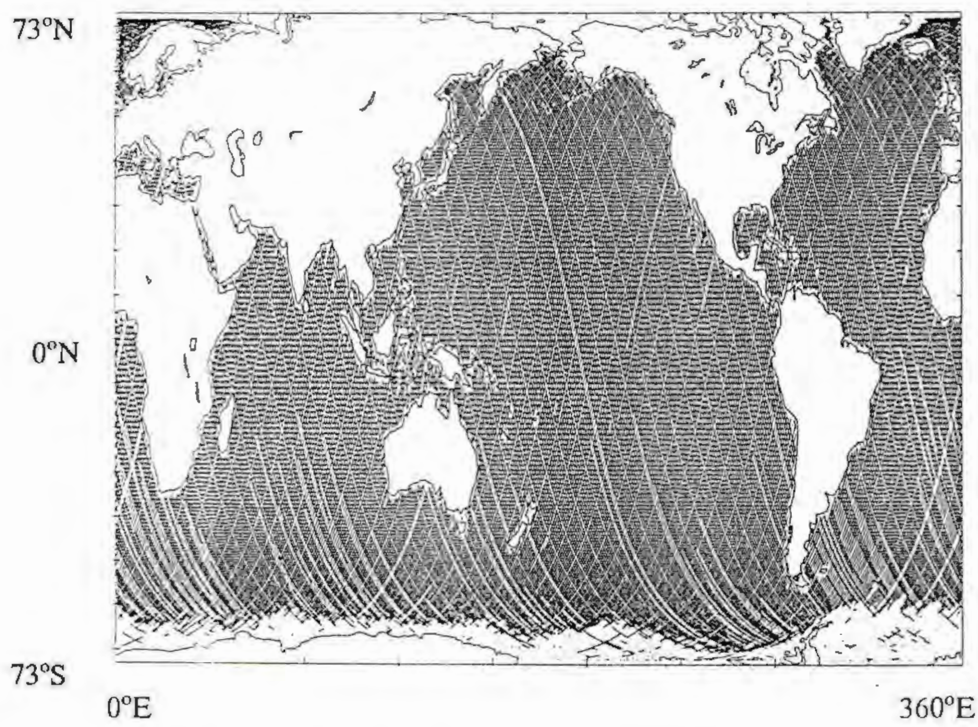
1985



GM Cycle 3

Days 137-159

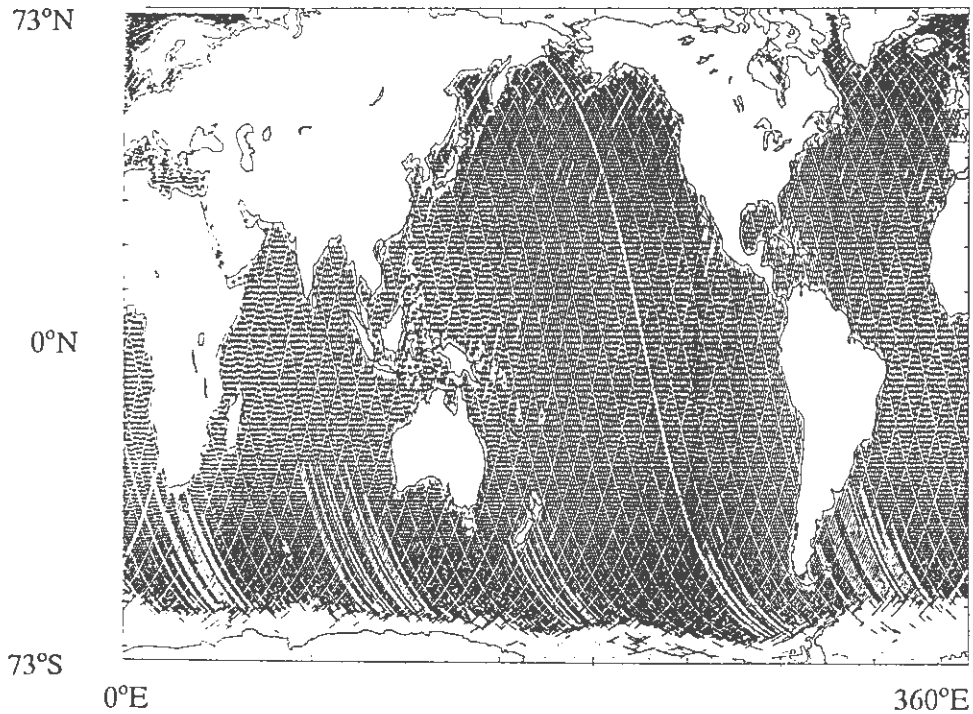
1985



GM Cycle 4

Days 160-182

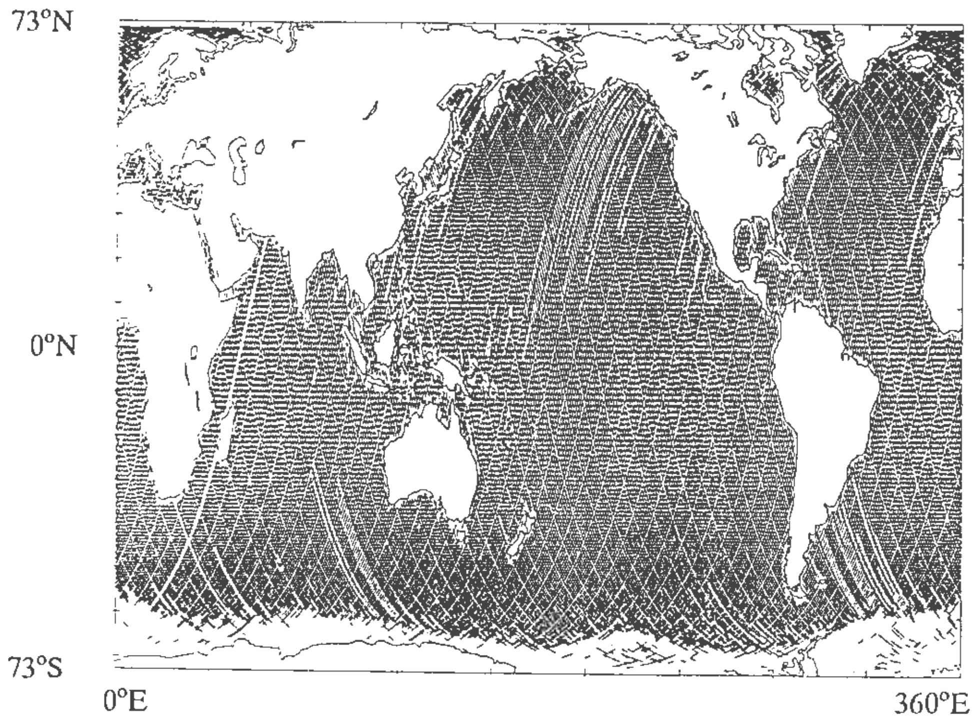
1985



GM Cycle 5

Days 183-205

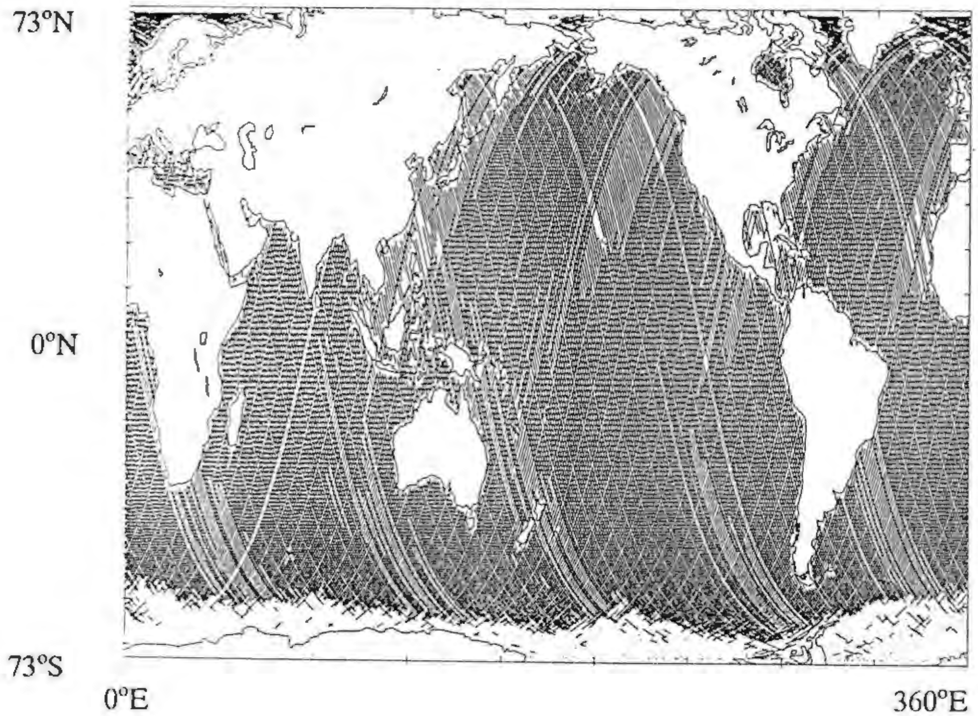
1985



GM Cycle 6

Days 206-228

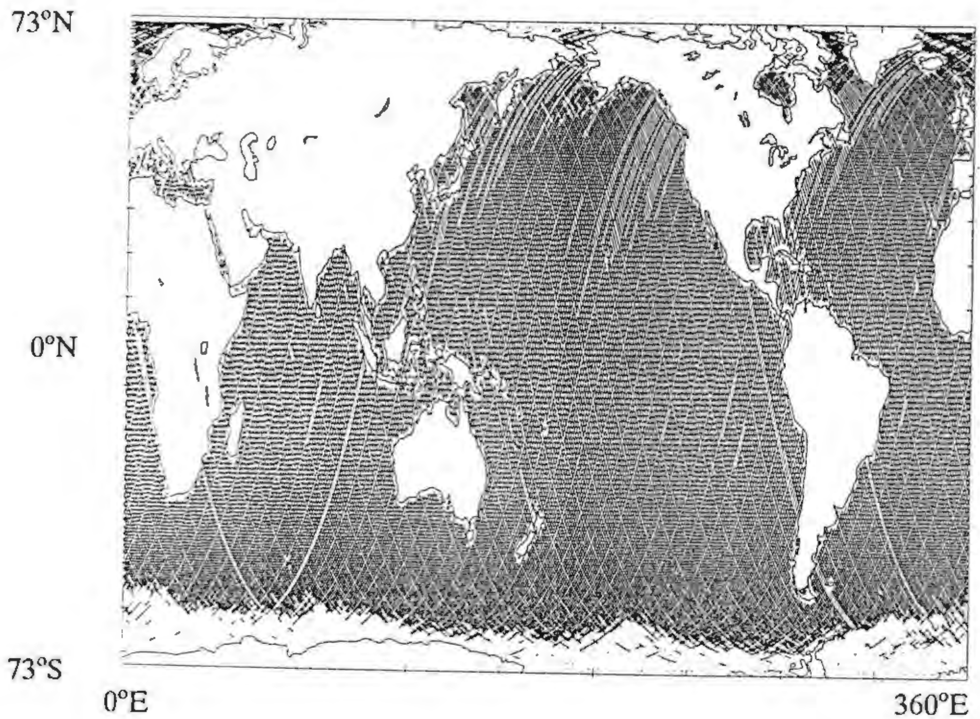
1985



GM Cycle 7

Days 229-251

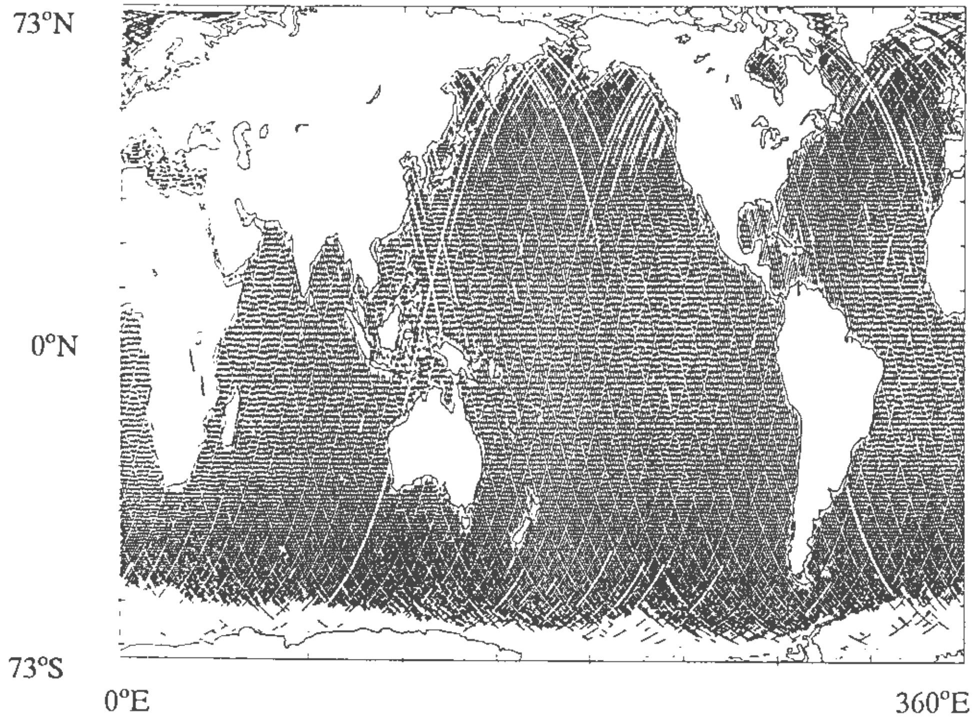
1985



GM Cycle 8

Days 252-274

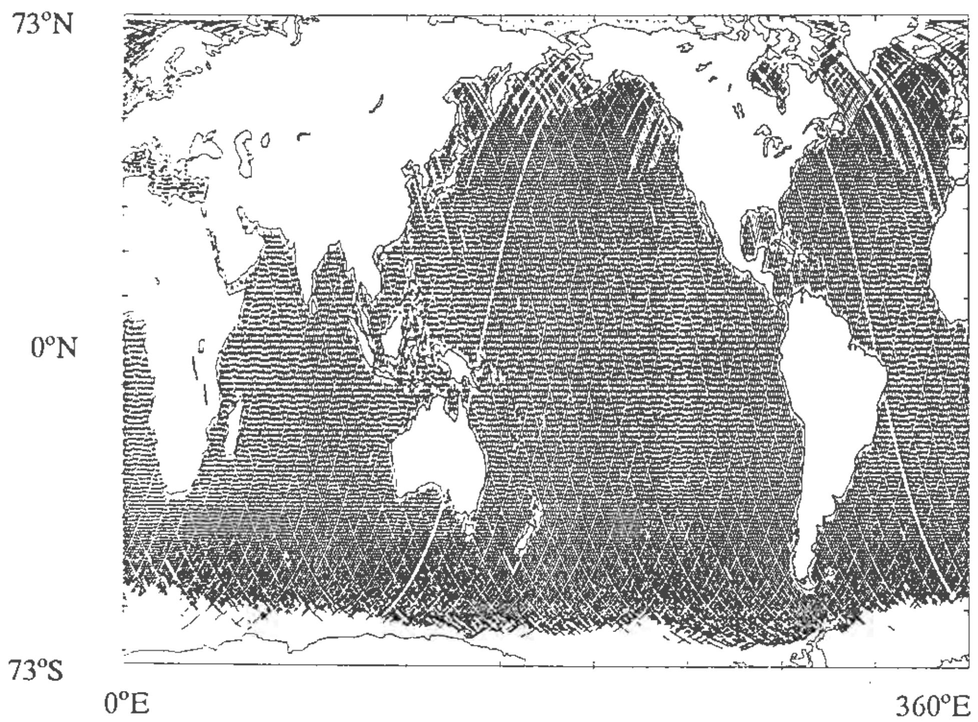
1985



GM Cycle 9

Days 275-297

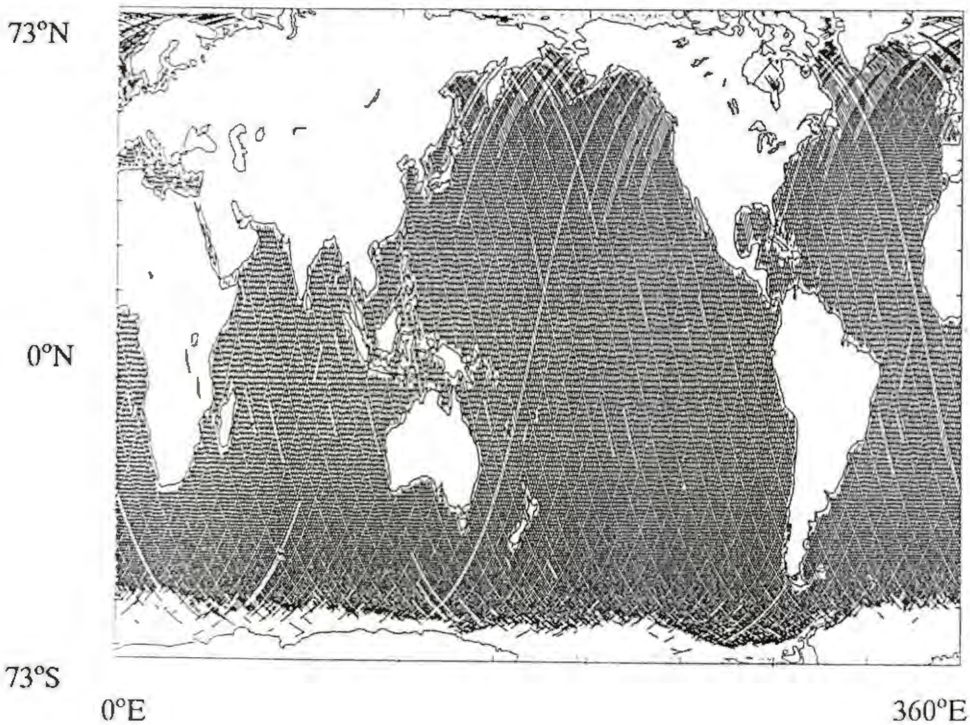
1985



GM Cycle 10

Days 298-320

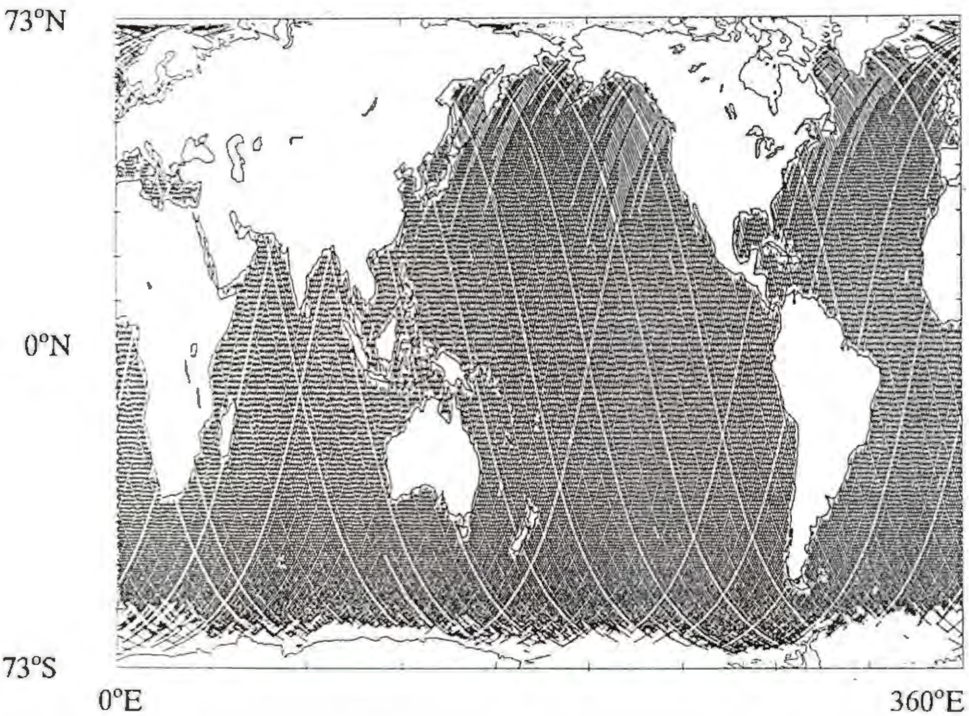
1985



GM Cycle 11

Days 321-343

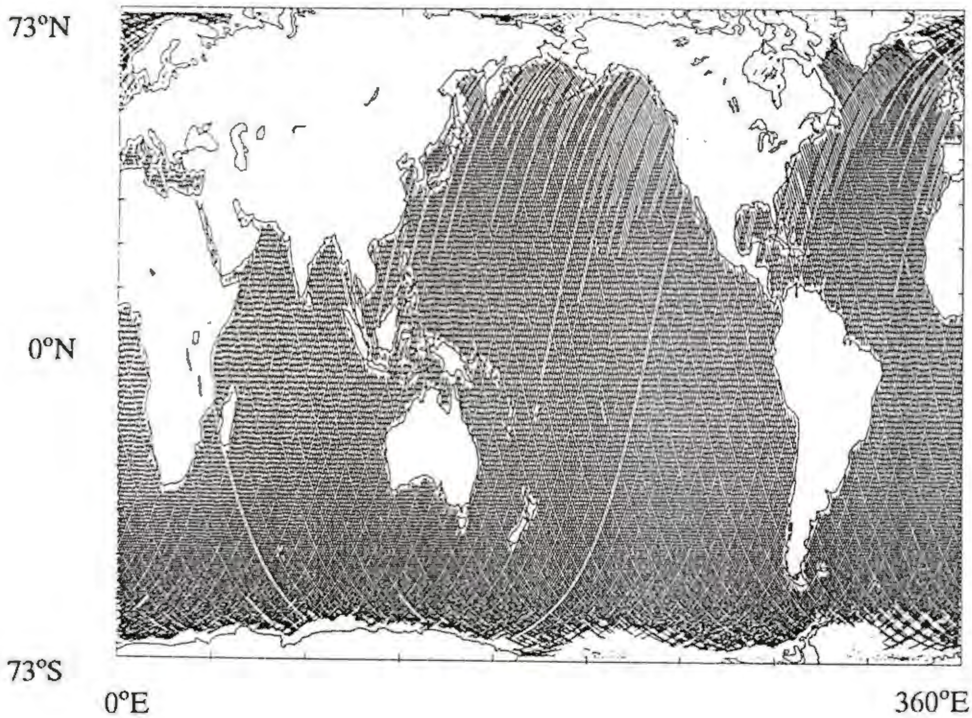
1985



GM Cycle 12

Days 324-001

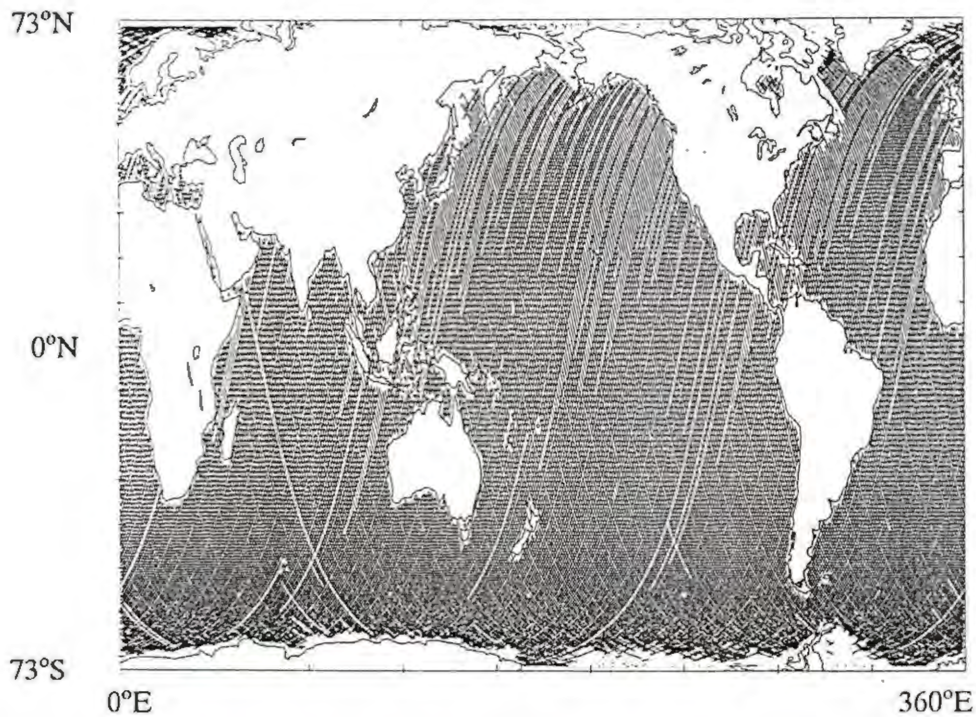
1985-86



GM Cycle 13

Days 002-024

1986



GM Cycle 14

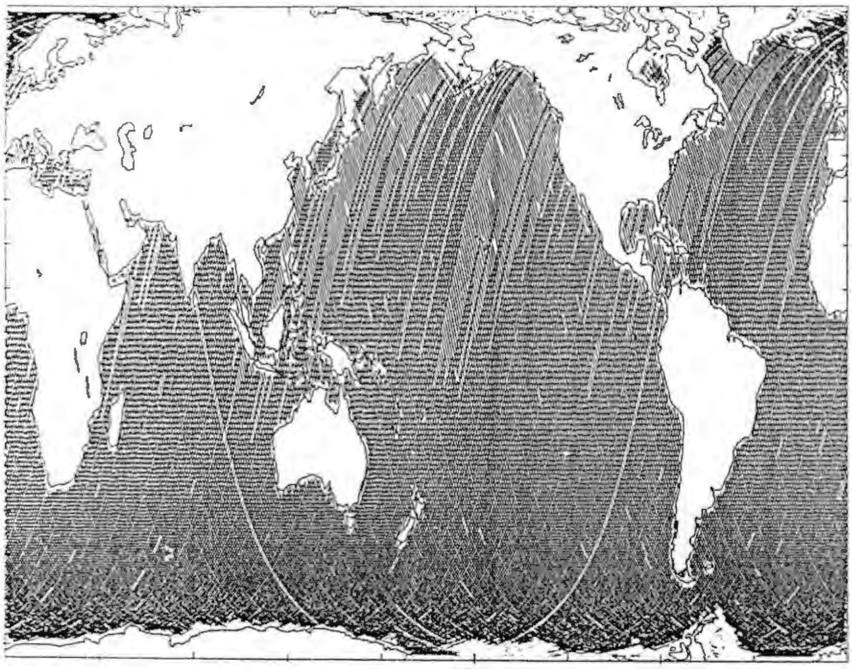
Days 025-047

1986

73°N

0°N

73°S



0°E 360°E

GM Cycle 15

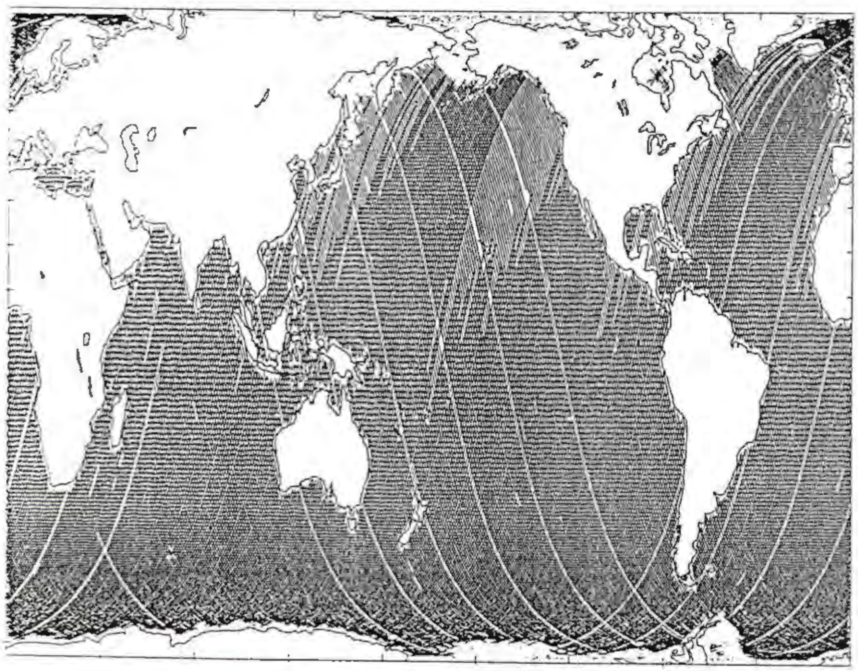
Days 048-070

1986

73°N

0°N

73°S

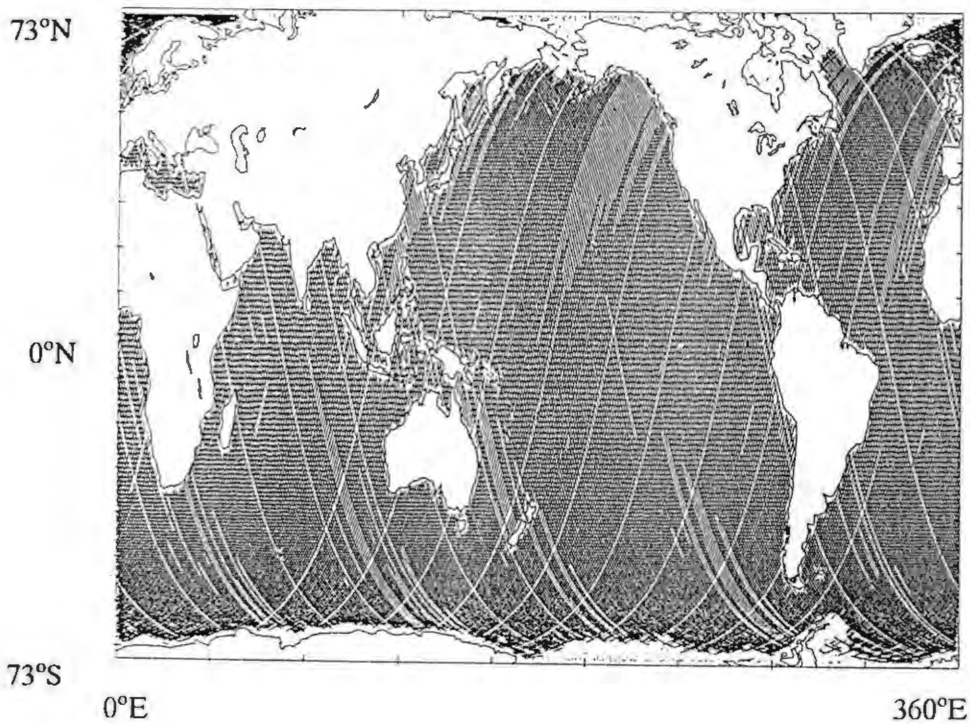


0°E 360°E

GM Cycle 16

Days 071-093

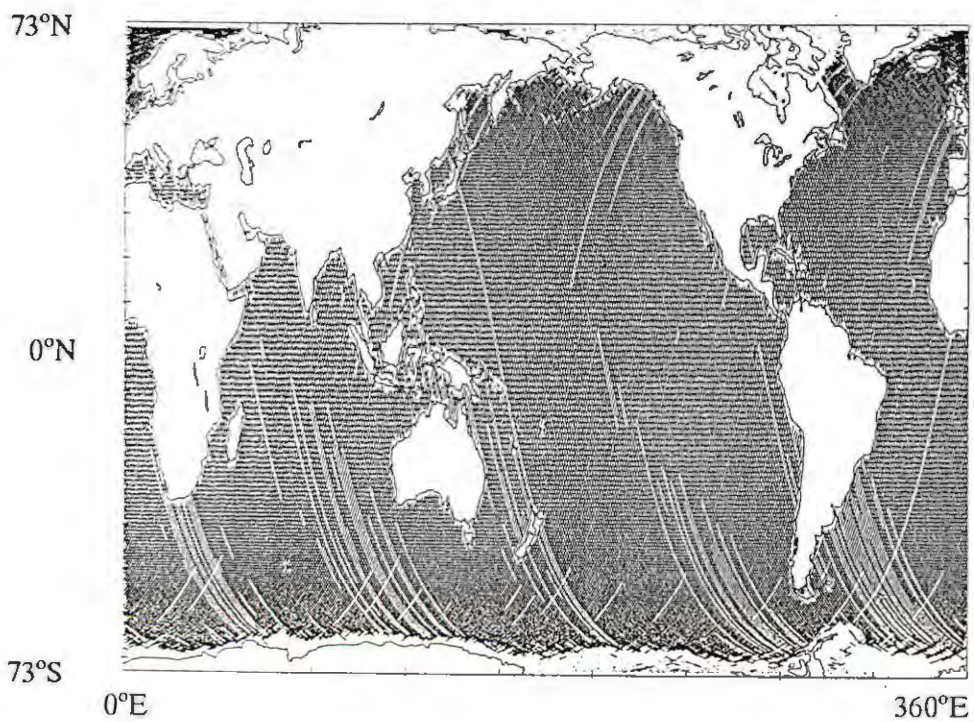
1986



GM Cycle 17

Days 094-116

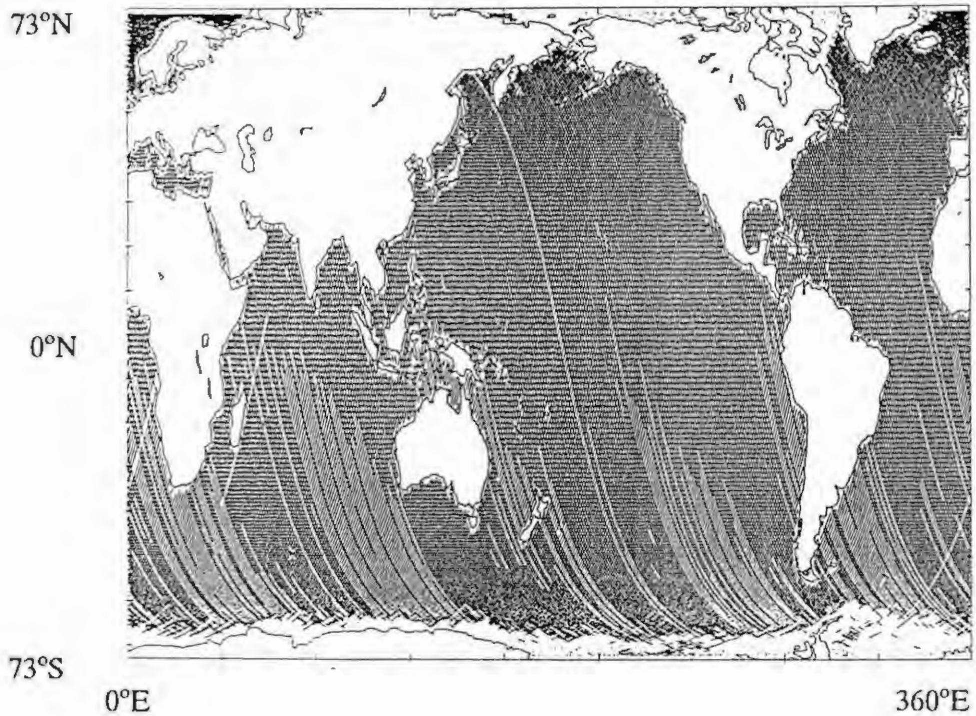
1986



GM Cycle 18

Days 117-139

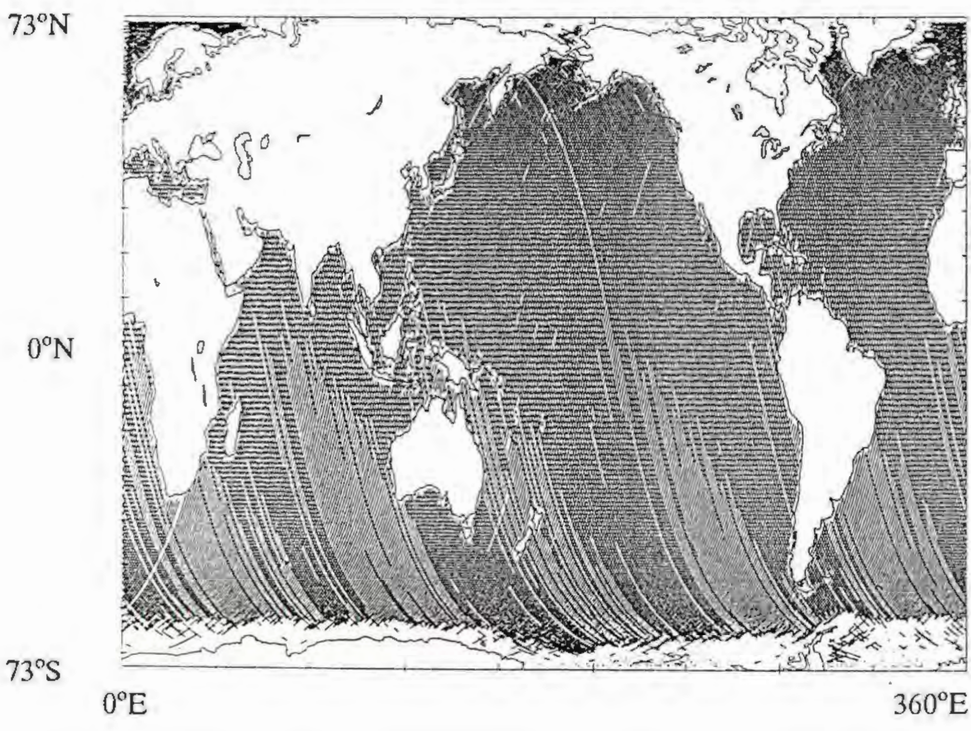
1986



GM Cycle 19

Days 140-162

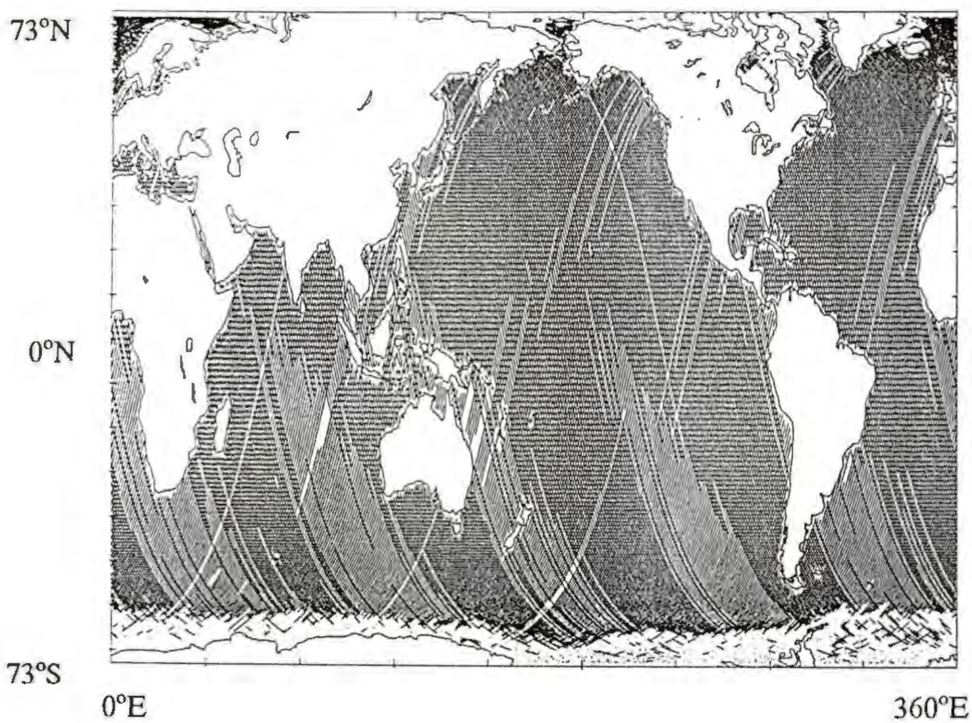
1986



GM Cycle 20

Days 163-185

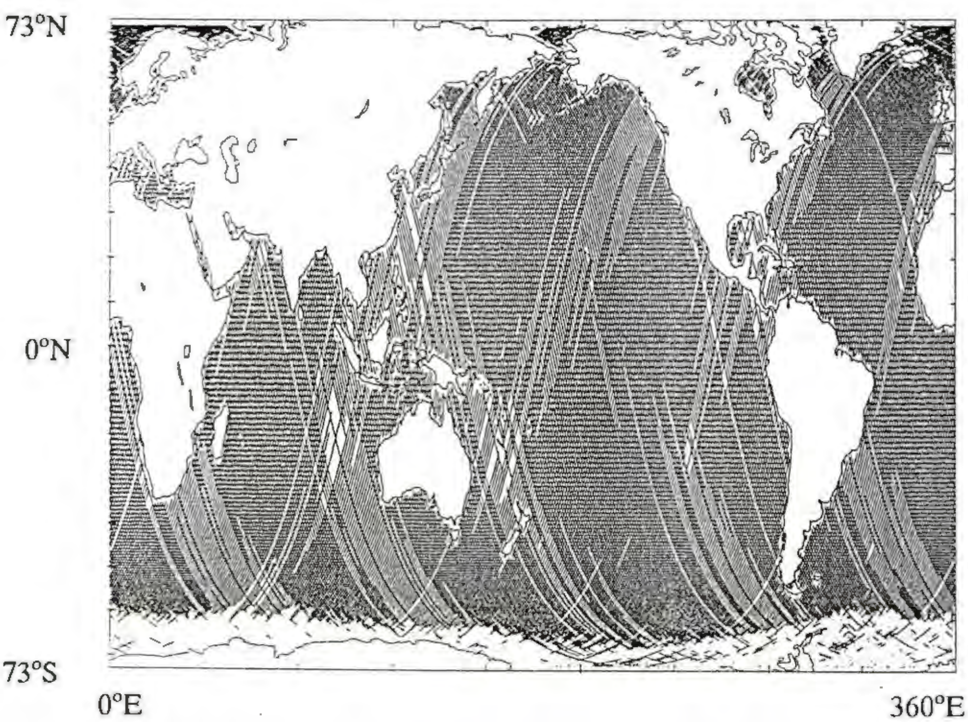
1986



GM Cycle 21

Days 186-208

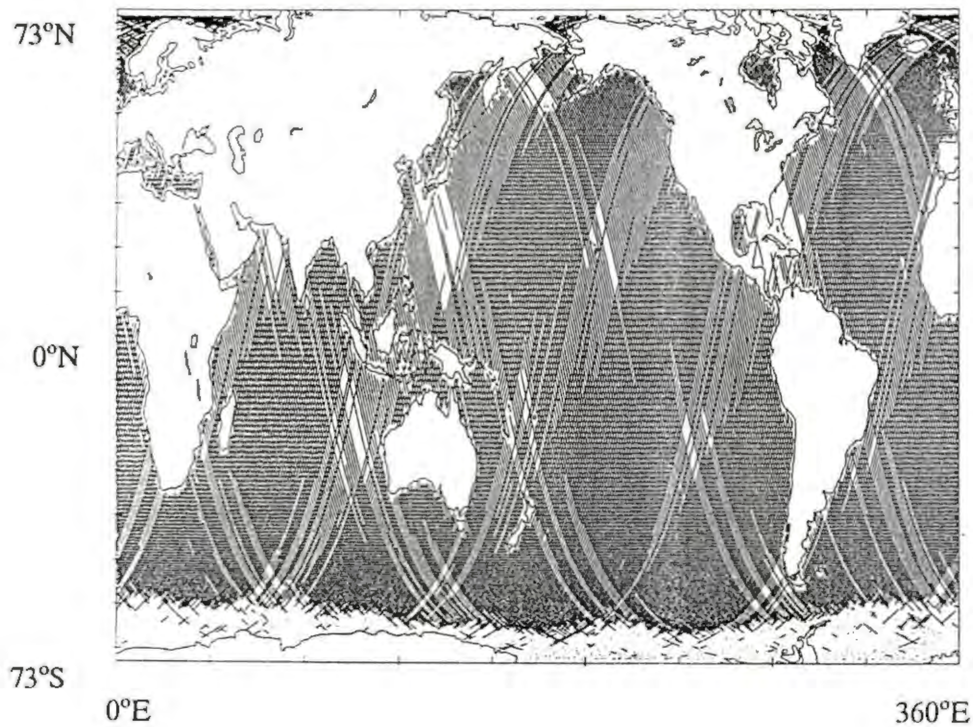
1986



GM Cycle 22

Days 209-231

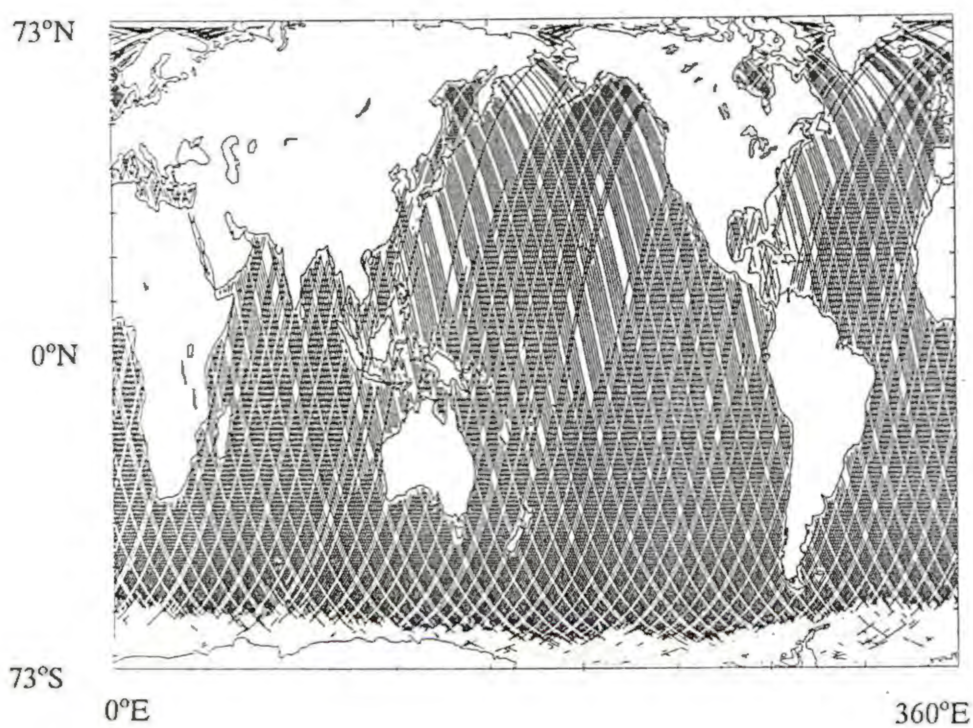
1986



GM Cycle 23

Days 232-254

1986



GM Cycle 24

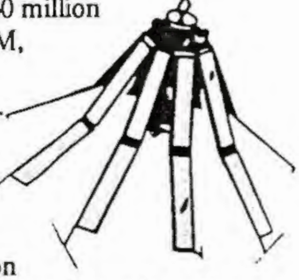
Days 255-273

1986

GEOSAT CROSSOVER DIFFERENCE DATA
from the Geodetic Mission

The National Oceanographic Data Center is pleased to announce availability of a global crossover difference data set derived from sea level observations collected during the first phase of operations of the U.S. Navy Geodetic Satellite (GEOSAT). GEOSAT's Geodetic Mission (GM) spanned the 18-month period April 1, 1985 to September 30, 1986. The satellite carried an altimeter designed and built by the Johns Hopkins University Applied Physics Laboratory (JHU/APL).

During the GM, the GEOSAT ground track did not repeat, thereby providing the densest coverage of any altimeter flown. Because of the military nature of its primary mission, the complete set of sea level data from the GM is classified and not available to the general public. However, crossover differences (sea level differences at ground track intersections) computed from these data can be released because they contain no geodetic information. A group within the NOAA National Ocean Service working at JHU/APL has constructed a global set of approximately 50 million GEOSAT crossover differences. These data include not only the initial 18-month GM, but also the first year of the subsequent GEOSAT Exact Repeat Mission, enabling computation of continuous, 2.5-year sea level time series spanning the two missions.



The GEOSAT crossover difference records (XDRs) are contained on 36 high density (6250 bpi), binary format magnetic tapes and are organized in 18 ocean regions (see Figure 1). The complete data set for each region occupies two magnetic tapes. In addition to sea level differences, the XDRs contain separate correction fields for tides, troposphere, and ionosphere together with other pertinent parameters and flags from the GEOSAT geophysical data records. No correction for orbit error is supplied, however, and adjustments must be performed to remove uncertainty in the satellite radial position. A copy of the *GEOSAT Altimeter Crossover Difference Record User Handbook* is provided with each order. The handbook includes details about how the data were processed, a complete record layout of the data, and a discussion of sea level variability applications based on the XDRs.

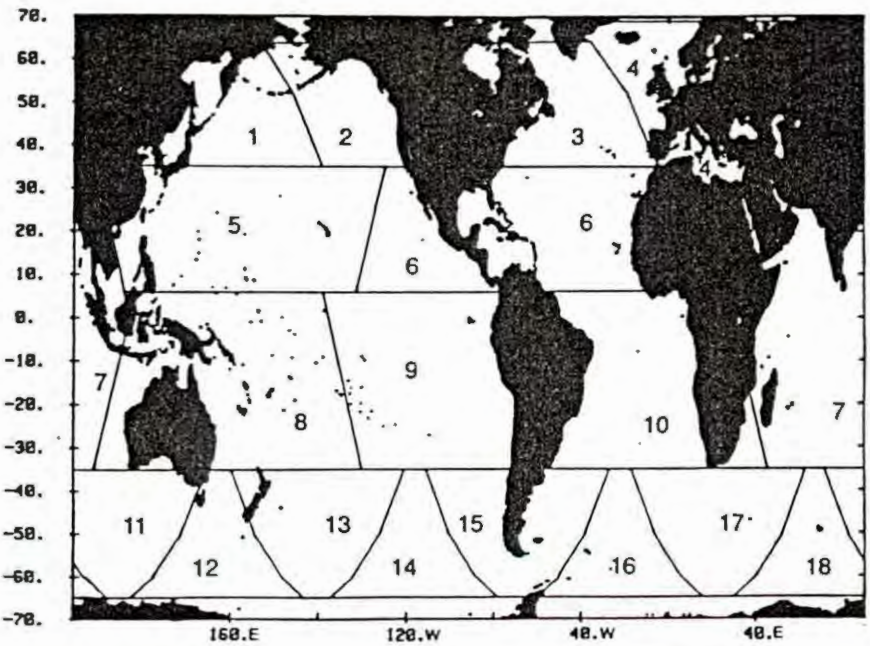


Figure 1. Geographic regions for the GEOSAT Crossover Difference Data Set. Data for each region are held on two magnetic tapes.

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

March 1991

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GEOSAT CROSSOVER DIFFERENCE DATA

DATA SELECTION:

☐ Please send me the complete GEOSAT Crossover Difference Data Set:
36 magnetic tapes (9 track, 6250 bpi, binary format).
Please provide the tapes in: VAX data structure ○; Hewlett-Packard data structure ○
Cost: $2593* *($71 per tape, plus $37 order processing/handling charge)*

☐ Please send me the GEOSAT Crossover Difference Data tapes for the following regions (two tapes per region):

Region 1 ○	Region 7 ○	Region 13 ○
Region 2 ○	Region 8 ○	Region 14 ○
Region 3 ○	Region 9 ○	Region 15 ○
Region 4 ○	Region 10 ○	Region 16 ○
Region 5 ○	Region 11 ○	Region 17 ○
Region 6 ○	Region 12 ○	Region 18 ○

***NOTE:** For geographic boundaries of regions, please see map on reverse side.*

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