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THE NORDA GEOSAT OCEAN APPLICATIONS PROGRAM

Measurements made by the GEOSAT microwave altimeter contain data on several oceanographic parameters. The Naval Ocean Research and Development Activity is conducting an operational demonstration that provides information on mesoscale features, wind speed, significant wave height, and sea-ice edge on a regular schedule. The methodology incorporates some innovative features, and results appear promising.

INTRODUCTION

The GEOSAT Ocean Applications Program combines several research efforts developed to evaluate and interpret GEOSAT-derived altimetry data. The function of the program is to demonstrate operationally the provision of oceanographic information to users on a regular schedule.

In addition to global nadir wind-speed magnitudes, significant wave heights, and sea-ice data, which are determined directly from the altimeter signal, mesoscale oceanic features in the northwest North Atlantic Ocean are reported after the analysis of sea-surface height residuals. The path of the Gulf Stream and the locations of warm- and cold-core rings are presented in a mesoscale product that is transmitted to the Fleet Numerical Oceanography Center twice weekly. A map of GEOSAT ice-index values for ground tracks north of 60 degrees north latitude and one for ground tracks south of 50 degrees south latitude also are generated and transmitted to the Naval Polar Oceanography Center each weekday. Specific techniques used by the GEOSAT Ocean Applications Program are described below.

Data gathered throughout the Ocean Applications Program operational demonstration flow from GEOSAT to the APL ground station, to the Naval Ocean Research and Development Activity (NORDA), and then to the Fleet Numerical Oceanography Center. GEOSAT is visible from the ground station for 10 to 20 minutes per pass during two clusters of passes (usually two or three passes each) per day. Since the number of orbits per day is not an integer, clusters are not separated by exactly 12 hours. Hence, the times at which the ground station observes the satellite fluctuate throughout the day. In most cases, it is possible to transmit all the data collected by GEOSAT since the previous cluster during the longest pass of a cluster, but in some cases it is necessary to split the data "dumps" between two (or more) passes. Because of this problem, and the "perishability" of the wind data, APL normally receives a few hours of data at a time and quickly processes and transmits

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the data to NORDA. The NORDA Data Record transmitted by APL consists of sensor-corrected altimeter data augmented with orbital elements and other information. NORDA's task is to process the data into oceanographic products and transmit them to the Fleet Numerical Oceanography Center where they are assimilated into environmental models or otherwise disseminated to Fleet users.

The information processing system hardware used by the GEOSAT Ocean Applications Program consists of two Gould/Systems Engineering Laboratories 32/27 32-bit minicomputers with associated peripherals, including International Imaging Systems (I^2S) image processing hardware. The software has four types of elements: communications and file management, real-time processing, objective processing, and interactive processing. The first element performs line-control functions for the two data links and transfers files between disks and the telecommunications lines. The second produces the scalar wind, significant wave height, and ice-edge products. The third involves such functions as earth location, land/sea determination, bad point editing and averaging, geophysical corrections, the calculation of height residuals, etc. The fourth covers operations that are used in the subjective generation of the mesoscale product and is comprised of I^2S 575 software, a proprietary interactive command interpreter, and an associated library of image processing functions designed to operate with I^2S Model 75 hardware.

The two telecommunications links both use 9600-baud dedicated telephone lines with KG-13 encryption/decryption devices. However, each line uses a different communication protocol. The line between NORDA and APL uses an IBM (standard) binary synchronous protocol with line control software written by APL (for both ends of the link). The hardware interface is based on the Gould/Systems Engineering Laboratory Model 9116 Binary Synchronous Line Interface Module. The line between NORDA and the Fleet Numerical Oceanography Center uses the X.25 protocol. The NORDA computer is interfaced to that line via a ComDesign TX-700 X.25 Packet Assembler/Disassembler. The Fleet Numerical Oceanography Center terminates the line into a Digital

Equipment Corporation PDP-11/70 computer, interfaced via an Associated Computer Consultants IF-11/X.25 Packet Assembler/Disassembler.

MESOSCALE ANALYSIS: OBJECTIVE COMPONENT

Modeled Geophysical Errors

The GEOSAT Ocean Applications Program analysis does not try to model all sources of geophysical error explicitly (APL removes instrument errors). Explicit models are not perfect, and the contributions of their errors to the total error budget would have to be considered in an analysis of the complete measurement system. Many geophysical error sources produce errors with wavelengths in the range of thousands of kilometers, much longer than the scale of mesoscale features. Because of the limited accuracy of potential models, it is preferable to use a "statistical" correction by fitting a straight line or other low-degree polynomial.

Some errors are in the mesoscale range or have significant energy at mesoscale wavelengths because of their size. The information processing system for the GEO-SAT Ocean Applications Program models ocean tides and electromagnetic bias and provides for the wet troposphere path length correction. Tides are accounted for with the Schwiderski model.[1] The electromagnetic bias is an apparent shift in sea-surface elevation owing to a difference in the strength of the reflection from the troughs and crests of ocean waves.[2] The primary effect is directly proportional to wave height and causes a range error of about 2 percent of the significant wave height at the frequency of the GEOSAT altimeter. The tracker itself is responsible for a similar bias; the combined effect is on the order of 5 percent of the significant wave height.

The path length error resulting from tropospheric water vapor may be significant. Its magnitude is on the order of 20 to 30 centimeters, with a variability of 10 centimeters in one region (some of it in the mesoscale wavelength range). The error may even be greater near an oceanic front, where sharp changes in sea-surface temperature are reflected in atmospheric gradients. No wet troposphere correction is used for the GEOSAT Ocean Applications Program.

Algorithms to calculate a wet troposphere path-length correction for GEOSAT using observations from the SSM/I radiometer (to be launched on the DMSP satellite in June 1987) were developed by Hollinger[3] and Lo.[4] These algorithms are based on linear combinations of the brightness temperatures measured by several channels of the SSM/I radiometer. Work begun at NORDA by R. J. Holyer has produced an alternate method based on multichannel infrared measurements, similar to the National Oceanic and Atmospheric Administration "split window" technique.[5,6] In some cases, estimates of total precipitable water can be derived from the magnitude of the brightness-temperature differences of two channels of an Advanced Very-High-Resolution Radiometer. To a close approximation, the range correction is given by

$$\Delta h_w = 6.43W, \qquad (1)$$

where W is total precipitable water.[7] Holyer's algorithm requires additional development.

Orbit Error and Other Unmodeled Geophysical Errors

Orbit determination is a major problem area in data analysis. GEOSAT is Doppler tracked via the Defense Mapping Agency's TRANET system, which yields orbits with crossover point consistency of better than 1 meter. However, these precise orbital elements are not available in time for GEOSAT Ocean Applications Program operational processing. The one-line "Z" format "skin-track" elements that are available promptly, combined with an ephemeris calculation that uses the full Brouwer formulation,[8] give orbits with residual errors in the 300- to 500-meter range. Most of that error is at wavelengths much longer than the scale of mesoscale features. However, a simple "tilt and bias" correction is inadequate because of the magnitude of the orbit error. Most of the error is concentrated in the first harmonic. An examination of the cubic term in the expansion of a sinusoid of this magnitude shows that a tilt and bias correction would fail to account for a nonlinear variation of approximately 115 centimeters over a 2000-kilometer arc (the size of the test area).

The Naval Space Surveillance System has developed an alternate method based on the analysis of a limited subset of TRANET data using the CELEST orbit determination program (R. Smith, private communication). The Naval Space Surveillance System receives TRA-NET data and computes short arc solutions for the few GEOSAT passes made each day over the northwest North Atlantic demonstration region. The resulting orbits are accurate to within a radial error of about 10 to 20 meters, which allows simple linear detrending.[9,10] Crossover-point adjustments may be used in the GEOSAT Ocean Applications Program during the Exact Repeat Mission.[11-15]

Table 1 gives an error budget for the GEOSAT mission based on postlaunch estimates (for the baseline mission) of the gravity, drag, solar pressure, station coordinates, and instrument noise uncertainties and lists the assumptions on which the table is based.[16] (See the article by Calman elsewhere in this issue for a discussion of corrections for instrument, propagation, orbit, and geoid errors as applied to altimeter data used to obtain sea-surface topography.)

Limitations of Objective Mesoscale Analysis

Three principal factors limit the detection and monitoring of mesoscale ocean features by the GEOSAT altimeter: (a) imperfect compensation for errors in the height residuals, (b) the lack of area coverage, and (c) problems owing to the satellite's ground-track laydown. The first factor imposes a limit on the absolute detectability of ocean features by the altimeter, while the other factors are limitations inherent in a single orbiting altimeter.

Table 1—GEOSAT measurement uncertainty.

Error Source	Uncertainty (centimeters 1σ) Baseline Mission	Uncertainty (centimeters 1σ) Extended Mission	Wavelength of Error (kilometers)
Altimeter			
Instrument noise	2	2	
Bias drift	2	2	(many days)
Time tag	0.2	0.2	20,000
Tracker bias	2	2	200–1,000
Media			
Electromagnetic bias	2	2	200–1,000
Skewness	1	1	200–1,000
Troposphere (dry)	0.7	0.7	1,000
Troposphere (wet)	6	3	200
Ionosphere	4	4	>1,000
Orbit			
Gravity	80	50	>10,000
GM	2	2	10,000
Atmospheric drag	10	10	10,000
Troposphere	1	1	10,000
Solar radiation pressure	10	5	10,000
Earth albedo	2	1	10,000
Earth/ocean tides	1	1	10,000
Station coordinates	10	10	10,000
Station/ spacecraft clocks	10	10	10,000
Higher order ionosphere	5	5	10,000
rss	83	54	

Major assumptions for baseline mission:[16]
1. TRANET tracking system, 40 stations
2. TRANET ground station oscillators perform to specifications
3. Altimeter data averaged over 1 second
4. $H_{1/3}$ = 2 meters, wave skewness = 0.1
5. Limited tuning of gravity field with GEOSAT TRANET data
6. 800-kilometer altitude
7. No anomalous data, no rain
8. ±3-millibar surface pressure from weather charts
9. 100-microsecond spacecraft clock

Major assumptions for extended mission:[16]
1. Same assumptions as baseline mission
2. Improved gravity, station location, and drag models based on GEOSAT tracking
3. Use of water vapor correction from SSM-1

All errors not correctly accounted for translate into height errors. While some errors have opposite signs and tend to compensate for one another, the net result is a height "noise" level that masks small variations in sea-surface topography.

The ground-track laydown of GEOSAT's orbit creates a different type of problem. Consecutive ascending (or descending) tracks are separated by about 25.1 degrees of longitude. Since the altimeter is a nadir-looking instrument with a relatively small field of view, there are very wide gaps in coverage during a one-day period. Even after one week there are large, diamond-shaped holes in the coverage.

A single altimeter does not give enough information to perform the mesoscale mapping task adequately, but the altimeter data can be supplemented by other information. The addition of the interpretive and inferential powers of a human analyst seems to be the most effective short-term approach to addressing the mesoscale information extraction problem.

MESOSCALE ANALYSIS: SUBJECTIVE COMPONENT

Interactive Concept

In an objective detection scheme, a decision is made as to whether a "signal plus noise" or "noise only" is present. There are two types of errors in this scheme. One results from detection system false alarms; e.g., the ground track actually undersamples the time-varying mesoscale field, a factor that is likely to contribute to such false alarms. Another type of error results from the failure to detect a signal; some mesoscale features that are actually present would not be found by any detection algorithm, simply because the altimeter does not "see" them.

The problem is one of "scene" analysis. The altimeter makes certain measurements of the mesoscale scene, from which its content is determined. It is clear that the application of other knowledge would be helpful. An understanding of ocean dynamics should facilitate the interpretation of events detected by the sensor. The most straightforward means of applying external knowledge (of oceanography) to this scene-analysis problem is to add a human expert. The GEOSAT Ocean Applications Program information processing system uses interactive image processing. This interactive aspect allows for the introduction of subjective decision making. The use of image processing supports the scene concept and suggests the use of imagery to support the decision-making process.

Synthesis of Data Types

It is natural to think of displaying altimeter data on a "picture" (e.g., satellite infrared imagery) of the area of interest. The area coverage provided by the imagery compensates for the lack of synopticity of the altimetry. Also, the thermal signatures of mesoscale features given by the imagery are useful to the analyst. However, the ability of the altimeter to penetrate cloud cover circumvents a limitation of infrared imagery. The altimeter can also yield information in areas where there is little temperature contrast or where surface-layer heat-

ing by the sun obscures thermal signatures. The ability of these sensors to complement each other has been well documented. [17]

Satellite observations give information about the sea surface. In-situ measurements, e.g., expendable bathythermograph (XBT) observations, are required to obtain detailed data about the vertical structure. Just as altimeter and infrared observations give complementary information about the sea surface, XBT observations provide information about the third dimension. The combination of data types, interpreted by a skilled analyst, serves to fill in the gaps that would exist if only one data source were available. And, where more than one data type is available, the combination provides supporting evidence to confirm or negate an interpretation.

ANALYSES OF OTHER OCEANOGRAPHIC PARAMETERS

Wind Speed and Wave Height

A detailed discussion of the wind speed and wave-height algorithms is provided in an article by Dobson et al. elsewhere in this issue.

Ice Index

The character of the backscatter from ice differs from the character of backscatter from water. Because the scattering from ice is primarily specular and comes predominantly from points near nadir, early backscatter is strong but the intensity of the signal decreases rapidly with time. Automatic gain control readings respond strongly to specular reflection from the smooth ice surface, and the automatic gain control signal has significantly more noise over ice than over water. The main reason for less noise over water is that the processing of altimeter returns on the satellite is designed to control the gain of the backscatter from ocean surfaces. Stronger returns from ice frequently cause saturation of the signal. [18]

An algorithm developed for GEOS-3 by Dwyer and Godin [19] augments automatic gain control data with information on the trailing edge of the return pulse provided by the average attitude specular gate. The GEOSAT altimeter does not have a specular gate, so the Dwyer-Godin algorithm is modified for GEOSAT to use voltage proportional to attitude, a parameter developed for the off-nadir-angle correction of wind-speed calculations. The resulting algorithm is given by

$$\text{Index} = \left[\frac{100 + \text{automatic gain control}}{100 \times \text{voltage proportional to attitude}} \right] \quad (2)$$

Because of the return-signal properties discussed above, this index has low values over water and high values over ice. The index stays in the 0.6 to 0.7 range over water and is generally greater than 1.0 (at times, much greater) over ice. Thus, it is possible to detect transitions between water and ice by thresholding the index.

It is likely that this index contains other useful information about the character of the ice as well.

PRODUCT PREPARATION

GEOSAT primary mission ground tracks define a tightly spaced global mesh, but the nonrepeating pattern of ground tracks does not allow the clear separation of the geoid from instantaneous topographic components of sea level, except in areas where a precise gravimetric geoid is known. A pre-existing reference geoid in the northwest North Atlantic Ocean led to the selection of a GEOSAT Ocean Applications Program area (Fig. 1) where the evaluation of the altimeter as an oceanographic tool could be undertaken.

Successive GEOSAT ground tracks translate westward by approximately 2700 kilometers at the equator. Generally, one ascending and one descending track intersect the test area daily. The pattern of ground tracks resulting from seven days of GEOSAT data is presented in Fig. 2. A sliding seven-day window of sea-surface height data represents a compromise between the temporal and spatial scales of mesoscale features associated with the Gulf Stream and the time and space scales of altimeter sampling.

GEOSAT traverses the Arctic region about 14 times a day. The ice index computed from the altimeter signal is plotted for all locations north of 60 degrees north latitude to generate a graphic sea-ice product. A similar southern-hemisphere product, for latitudes south of 50 degrees south latitude, is also prepared. Values of scalar wind speed and significant wave height are calculated globally (over the ocean).

The formulation of the mesoscale products begins immediately after the computation of sea-surface height residuals. The residuals are plotted along GEOSAT ground tracks (Fig. 3). Discernible mesoscale features are identified and their positions are stored. The mag-
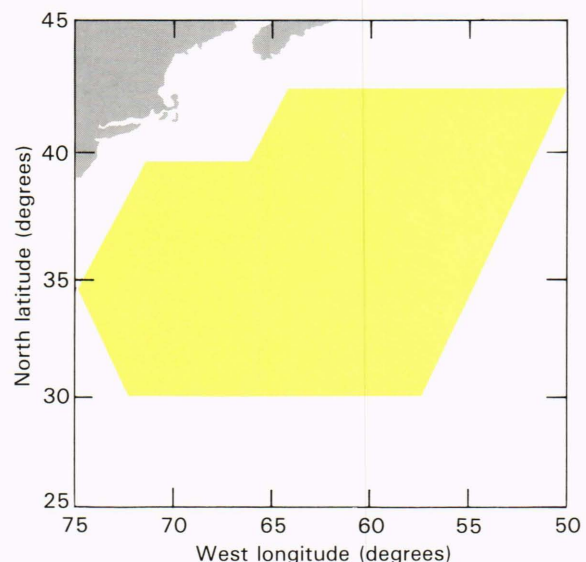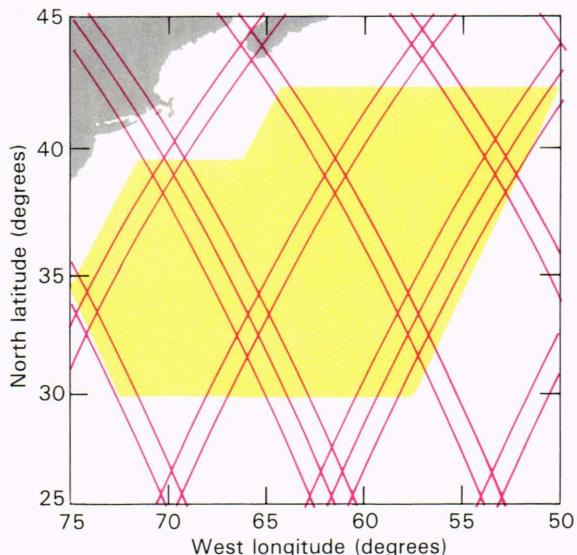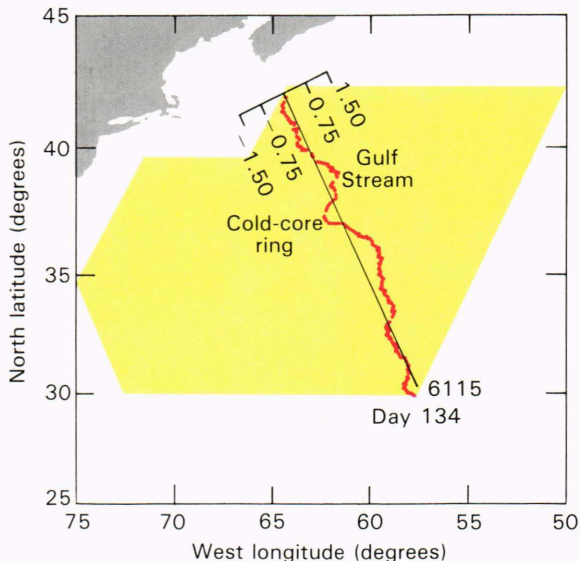

Figure 1—Mesoscale test area for the GEOSAT Applications Program.
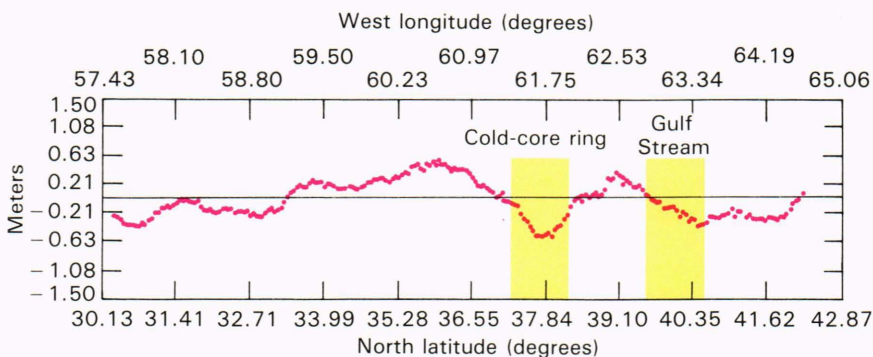
Figure 2—Seven days of GEOSAT ground tracks passing through the GEOSAT Ocean Applications Program mesoscale test area.

Figure 3—A sea-surface height-residual profile plotted along a ground track.

Figure 4—An X–Y plot of a sea-surface height-residual profile.

nitude of geostrophic currents associated with height residuals may be inferred.

Alternatively, a sea-surface height-residual profile may be plotted as in Fig. 4. The Gulf Stream appears in the residual profile in various forms, depending on the strength of the Gulf Stream and its angle of intersection with the GEOSAT track. A GEOSAT track perpendicular to the Gulf Stream will show a distinct Gulf Stream signature. Generally, the southern edge of the Gulf Stream appears as a relative high, followed by a decrease in the magnitude of the height residual. The northern wall of the Gulf Stream is located at the base of a sharp height-residual decrease. Geostrophic current speeds inferred by the southern edge to the north wall decrease in sea-surface height, and the distance between the two is comparable to observed Gulf Stream magnitudes.

Warm-core rings appear in sea-surface height residuals as isolated highs surrounded by two lows north of the Gulf Stream. Anticyclonic flow is associated with this topography. Warm-core rings are significant topographic features with sea-surface height signatures greater than 0.4 meter. Cold-core rings, which exhibit cyclonic circulation, are represented by isolated lows with larger values on either side. Sea-surface height-residual ranges generally exceed 0.6 meter in a cold-core ring. Because GEOSAT passes over the edges of rings more often than over their centers, lower sea-surface height-residual ranges are selected as possible features and are compared to nearby passes.

The positions of significant mesoscale features selected during a seven-day period are recalled and plotted on a base chart. Positions indicating like features on adjacent tracks are connected to show the path of the Gulf Stream and the locations and extents of cold- and warm-core rings. Emphasis is placed on the most recent sea-surface height data. Less than 50 percent of the Ocean Applications Program area is traversed by GEOSAT during a seven-day period, and other sources must be accessed to complete the mesoscale product.

The primary source of complementary data is a sea-surface temperature image from the most recent pass of the National Oceanic and Atmospheric Administration satellite TIROS-N, acquired and processed by NORDA.

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The image is usually less than 24 hours old. Where the Gulf Stream and warm- and cold-core rings are discernible on the sea-surface temperature image, positions of the north wall and southern edge of the Gulf Stream and ring locations are digitized from the screen and printed out. The analyst then plots these positions on the base chart and uses them to compare to and supplement sea-surface height-determined positions. When the sea-surface height and sea-surface temperature image positions do not agree, the former position is selected as the correct location.

A supplemental source of data is the XBT measurements forwarded to the Fleet Numerical Oceanography Center by ships and aircraft. The position, sea-surface temperature, and subsurface temperature profile of each are noted on the base chart. This information is used to confirm sea-surface height and temperature image data and to fill in gaps that may exist. The resulting base chart becomes a completed mesoscale product.

A message composed of Gulf Stream north-wall and southern-edge latitudes and longitudes and warm- and cold-core ring center positions and radii is compiled using sea-surface height and sea-surface temperature image locations. The source of the data—whether altimeter, sea-surface temperature, or estimated—is included in the message. A mesoscale product map (e.g., Fig. 5) is generated as a quality-control measure. Both products (the message and mesoscale product map) are generated twice each week and transmitted to the Fleet Numerical Oceanography Center for incorporation into its Gulf Stream analysis.

Nadir wind-speed magnitudes, significant wave heights, and sea-ice index values are transmitted shortly after receipt at NORDA. Following scrutiny of the ice index values, including comparison to sea-surface temperature images, a graphic sea-ice product is generated from ice index values along GEOSAT ground tracks north of 60 degrees north latitude (see Fig. 6). The ice product is transmitted daily to the Naval Polar Oceanography Center for use in compiling daily ice maps.

STATUS AND PLANS

NORDA produced the oceanographic products during the 18-month primary mission of GEOSAT, which was completed in September 1986. The Regional Energetics Experiment, using underflights to GEOSAT along with other data collection techniques and numerical modeling, is investigating the dynamic relationship between sea-surface temperature, subsurface temperature, and sea-surface height residuals (see the article by Mitchell et al. elsewhere in this issue). Mesoscale products also show some correlation between significant wave-height variations and the presence of frontal boundaries.

The preliminary evaluation of the Ocean Applications Program mesoscale product by the Naval Eastern Oceanography Center is favorable. The Center uses the data primarily as indicators for possible cold-eddy activity in locations where surface thermal signatures are not visible in infrared imagery. On several occasions, the product
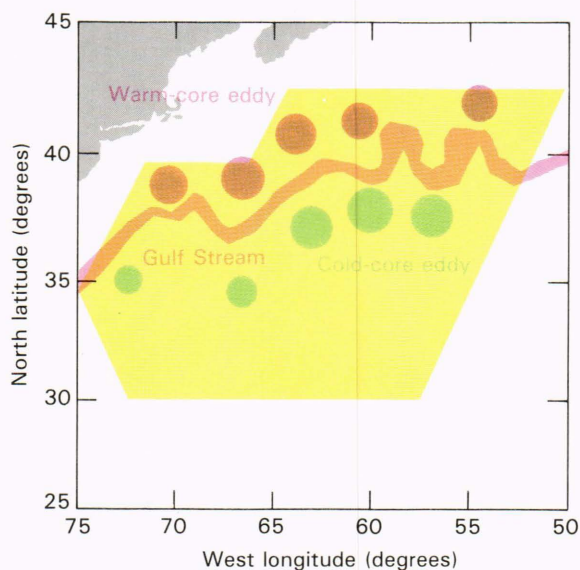

Figure 5—A sample mesoscale product map for the GEOSAT Ocean Applications Program.

located a cold eddy that was subsequently verified by satellite imagery or bathythermograph data. Generally, the Center finds that more eddies, both warm and cold, are evident in the altimeter product than in infrared imagery. A good correlation has also been found in the general position and trend of the Gulf Stream between data. However, the altimeter does not seem to resolve high-amplitude, very-short-wavelength meanders (60 to 120 nautical miles).[20]

The Naval Polar Oceanography Center also finds the GEOSAT ice products useful and reports that the ice products are particularly valuable when cloud cover precludes the use of visual or infrared imagery. The 7-kilometer resolution is better than that derived from the Scanning Multichannel Microwave Radiometer, and the scale and projection of the graphic products are identical to those of the Center's working charts.[21]

Following the end of the primary mission, GEOSAT was maneuvered into a near-circular 17-day exact repeat orbit, as proposed by Mitchell.[22,23] From this orbit, GEOSAT is sampling the oceans with a grid of 244 revolutions spaced 165 kilometers apart at the equator. The time spacing between adjacent tracks will remain three days, while the entire grid will begin to repeat after approximately 17 days. This repeating grid will be maintained to a lateral ground-track precision of ±1 kilometer. Differences of one pass relative to the ensemble mean of all passes along a given track will then allow for the global recovery of sea-level fluctuations due to mesoscale oceanography without the need to resort to regional geoids.

During the first year of this GEOSAT-Exact Repeat Mission, plans call for the objective processing of wind, waves, and ice-edge products to be implemented at the Fleet Numerical Oceanography Center. GEOSAT data will continue to flow from APL through NORDA to the Center. Initially, mesoscale analysis will be carried

Figure 6—A sample ice-index graphic product for the GEOSAT Ocean Applications Program.
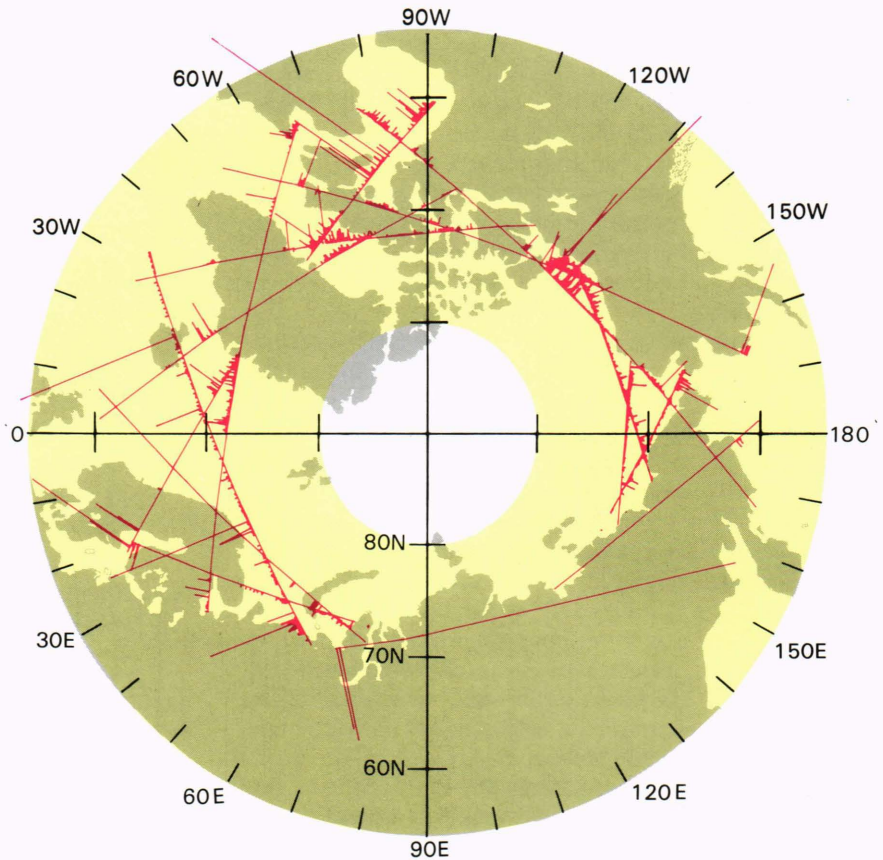
out only for the northwest North Atlantic area; however, by the end of the first year of the Exact Repeat Mission, the feasibility of objectively mapping sea-surface topography or topographic fluctuations in other areas (e.g., the Kuroshio region) using an ephemeris computed by the Navy Astronautics Group will be examined. If successful, these objective techniques will be transferred from NORDA to the operational Navy within the second year of the Exact Repeat Mission.[24]

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