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THE NAVY GEOSAT MISSION: AN OVERVIEW

The limited GEOS and Seasat data sets have proven the satellite radar altimeter to be a versatile and powerful tool for the remote sensing of the oceans. Altimetry data support Navy requirements in the areas of geodesy, the operational measurement of fronts and eddies, winds, waves, and ice topography. The Navy GEOSAT Mission is working to satisfy these requirements by producing a dense, global altimetric database. This article gives an overview of radar altimetry, the Navy GEOSAT Mission, and ongoing applications of the data.

BACKGROUND

The GEOSAT[1] radar altimeter measures the distance between the satellite orbit and the subsatellite point on the ocean surface with a precision of a few centimeters. Since the shape of the orbit can be measured independently, the altimeter gives a precise measurement of the shape of the ocean's surface along a line under the satellite.

In the absence of disturbing forces, the ocean flows under the influence of gravity so that its surface conforms to the shape of the earth's geopotential field. The altimeter then directly measures the marine geoid. The process is disturbed both by rapidly changing oceanographic features (e.g., rings and eddies) and slowly varying components of ocean circulation (e.g., major currents such as the Gulf Stream). A long-term average of altimeter data reduces the impact of the "noise" introduced by these oceanographic features and gives a "mean surface" that is a good approximation of the marine geoid in many areas (Fig. 1). The direction of the normal to the mean surface, the "local vertical," is an important term in navigation models. The need for precise navigation has made geodesy the most important application of radar altimeter data.

Oceanographic features can be recovered from the altimeter data by subtracting the long-term mean surface (Fig. 2). Recent research has indicated that the time-dependent mesoscale (50- to 300-kilometer) features (e.g., fronts, rings, and eddies) that can be sensed by the altimeter have a strong impact on underwater acoustic propagation. The operational generation of these environmental products is a maturing application of radar altimeter data.

Finally, the significant wave height and reflection coefficient of the ocean surface can be determined by measuring the leading-edge slope and amplitude of the reflected radar pulse. Ground processing allows the surface wind speed to be derived from the reflection coefficient.

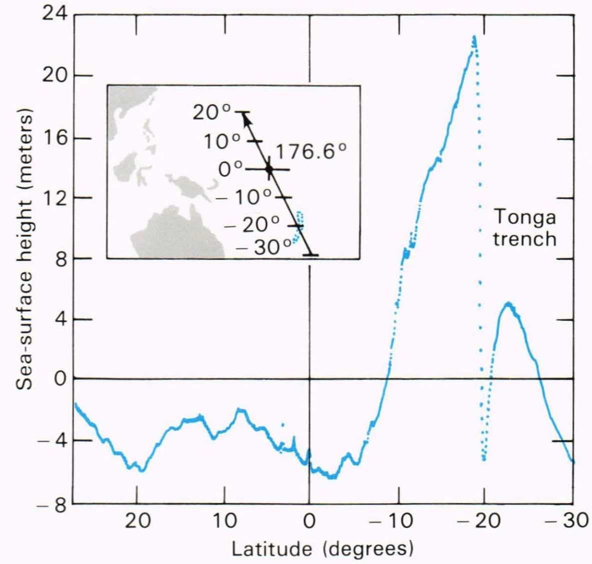

Figure 1—The geoid feature in the ocean topography across the Tonga Trench as measured by the GEOSAT altimeter (see the article by Cheney in this issue).

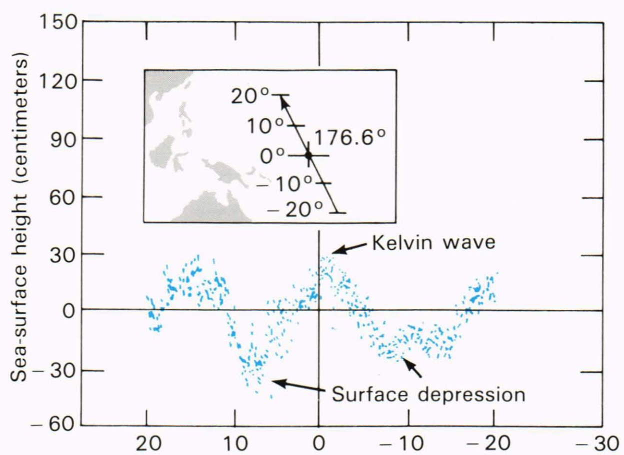

Figure 2—Mesoscale oceanographic features in the difference of two repeat-orbit passes over the Tonga Trench (see the article by Cheney in this issue).

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ALTIMETER MISSIONS

The in-orbit measurement precision of the altimeter has improved from the 1-meter precision accomplished by the Skylab mission to the 10-centimeter precision realized by Seasat (Fig. 3). Unfortunately, the Seasat data return was limited to 90 days because of a power system failure in the spacecraft.

The GEOSAT altimeter incorporates a number of design changes that have resulted in improved measurement precision. Its in-orbit performance indicates a precision approaching 3 centimeters for moderate wave heights.

The Navy Remote Ocean Sensing System, the next-generation Navy mission, will implement a completely redundant altimeter with GEOSAT measurement precision. Advances in microminiaturization have resulted in an instrument of about the same weight and size as the nonredundant GEOSAT instrument.

The Ocean Topography Experiment satellite, a future NASA mission, will measure altitude using both C- and Ku-band frequencies. The measurements will be combined to achieve a 3-centimeter precision ranging independent of the long-wavelength ionospheric propagation errors that have contaminated basinwide ocean-circulation measurement data taken with previous altimeters.

Altimeter missions are also proposed by the European Space Agency for 1990 and the NASA Space Station Earth Observing System for late 1993.

THE GEOSAT PRIMARY MISSION

GEOSAT's primary mission is to provide the dense global grid of altimeter data required to improve the determination of the earth's gravitational field. The secondary mission is to detect mesoscale oceanographic features in a timely manner.

The mission uses a single instrument, the radar altimeter, with a 3.5-centimeter precision at a 2-meter significant wave height. Dual-frequency Doppler tracking allows precise satellite-orbit determination. Data are stored on board the spacecraft for approximately 12 hours and are then transmitted to the Satellite Tracking Facility at APL. The GEOSAT ground station preprocesses the data for distribution to a variety of users. Companion articles elsewhere in this issue describe the systems components: the radar altimeter (MacArthur et al.), the spacecraft (Frain et al.), and the ground system (Jones et al.).

The satellite was launched on March 12, 1985, into an 800-kilometer altitude, 108-degree inclination orbit that generated 3-day near-repeat ground tracks. At the completion of the 18-month-long primary mission on September 30, 1986, the average spacing of the ground track grid was 4 kilometers. The altimeter had then accumulated 270 million observations of sea level along 200 million kilometers of the world's oceans. Having completed the primary mission, GEOSAT was maneuvered into a 17-day exact repeat orbit optimized for oceanography to begin the GEOSAT Exact Repeat Mission. Data from this mission are helping to satisfy the need for measurements of oceanographic features that are critical to Navy operations.

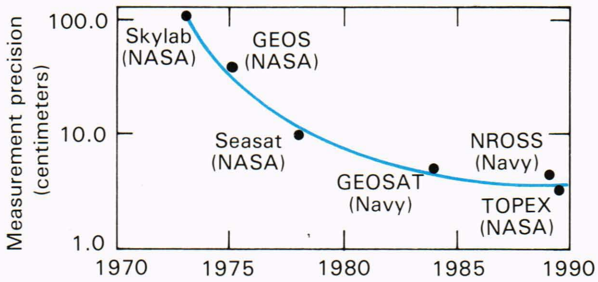

Figure 3—The evolution of satellite altimetry precision.

The Navy Requirement for the GEOSAT Primary Mission

The Navy requirement for geodesy information dates back to the early 1960s when submarine commanders discovered the need for more accurate navigation data to perform their mission. Initially, the data came from ship surveys that covered key areas of the major ocean basins, mapping bathymetric features and geodesy variations. The process was slow, expensive, and incomplete. With the advent of microwave remote-sensing techniques in the late 1960s, the mapping of key environmental parameters from space became possible. The ability to cover large areas of the globe quickly, accurately, and repeatedly justifies this expensive space-qualified sensor.

The improvement in the altimeter's ability to measure the marine geoid coincided with a growing Navy requirement for more accurate geodesy data. Increased accuracy requirements for Advanced Submarine Launched Ballistic Missile systems have resulted in an extensive effort to understand and reduce a variety of error sources. As these error sources are reduced, the geodetic/geophysical error contributors become an increasingly large percentage of the total system error budget. A reduction of the error budget can be realized by extensive ship and and satellite surveys to achieve the necessary improvement to the earth gravitational models. However, a high-density intermediate- and low-frequency gravity database is required worldwide that is impractical to obtain by ship survey. As a consequence of the early loss of Seasat, GEOSAT was conceived within the Navy in late 1978 to produce a detailed worldwide geodetic database by 1985—something no other proposed system could do.

The primary mission of GEOSAT was therefore to provide a homogeneous high-density intermediate- and long-wavelength gravity database over the global ocean. The mission directly supports

1. Improved map compensations for geoid height, vertical deflections, and in-flight gravity;
2. Definition of specific geophysical/geologic areas for more detailed ship survey follow-up;
3. Detection of the possible bathymetric hazards to submerged navigation (an existing Defense Mapping Agency requirement).

The mission was to be satisfied by three 6-month data sets with an equatorial satellite subpoint separation of approximately 10 kilometers.

Partial justification for the GEOSAT mission resulted from the cost benefit to be realized. The entire GEOSAT program (i.e., altimeter, spacecraft, launch, and 3-year mission operations) is projected to cost approximately $60 million. Using GEOSAT data as a reconnaissance survey upon which future ship-survey track spacing could be planned was estimated in 1980 to save 16 ship-years of survey time at a cost of $60 million. Additionally, GEOSAT will detect 98 percent of the bathymetric hazards to submerged navigation during a 6-month operation. (Ocean Survey Program ships can provide only 49 percent of the data in major operating areas because of track spacing.) It is estimated that the ship survey time saved is 30 ship-years at a cost of $280 million (1980 dollars). GEOSAT has already shown an extraordinary cost benefit to the Navy.

During the early GEOSAT planning stages, it became obvious that other scientific disciplines could benefit from altimeter measurements. Seasat data analysis was showing an important relationship between altitude and major oceanographic features (e.g., current boundaries and mesoscale eddies). In February 1982, the Navy established a secondary GEOSAT mission to support tactical mesoscale oceanography, which was not to interfere with the geodesy mission during the first 18 months of operation. In October 1986, the satellite was maneuvered into a 17-day exact repeat orbit designed to optimize the measurement of tactical oceanography. The Exact Repeat Mission is to continue for as long as the satellite operates.

GEOSAT Primary Mission Data Flow

Radar altimeter data are stored on board the spacecraft for approximately 12 hours and are then transmitted via S-band telemetry to the Satellite Tracking Facility at APL (Fig. 4). After demodulation and bit synchronization, the encrypted data are stored by analog tape recorders. Post pass, the archive tape is read and the data are frame synchronized and stored on computer disk for later processing.

No single-point-failure redundancy is incorporated in in the telemetry and command chains at the APL facility. This allows system operation using the single ground station without loss of data or command opportunity during the entire 18-month geodesy mission.

Precise orbital ephemeris for the user is computed by the Naval Surface Weapons Center, Dahlgren, Va., using Doppler beacon tracking data obtained by the Defense Mapping Agency TRANET Network. Navy Space Surveillance Activity (radar track) elements are used by the APL facility for alerts and antenna pointing.

Three primary data products are provided by the APL facility for user applications:

1. Sensor Data Record—a classified computer-compatible tape containing measured altitude, significant wave height, wind speed, and automatic gain control, plus corrections for satellite and instrument errors. After generation, the tapes are validated for independent quality control; during the primary mission period, they were delivered to the Naval Surface Weapons Center within two weeks of data receipt.
2. Naval Ocean Research and Development Activity (NORDA) Data Record—a classified data record (with contents similar to the Sensor Data Record)

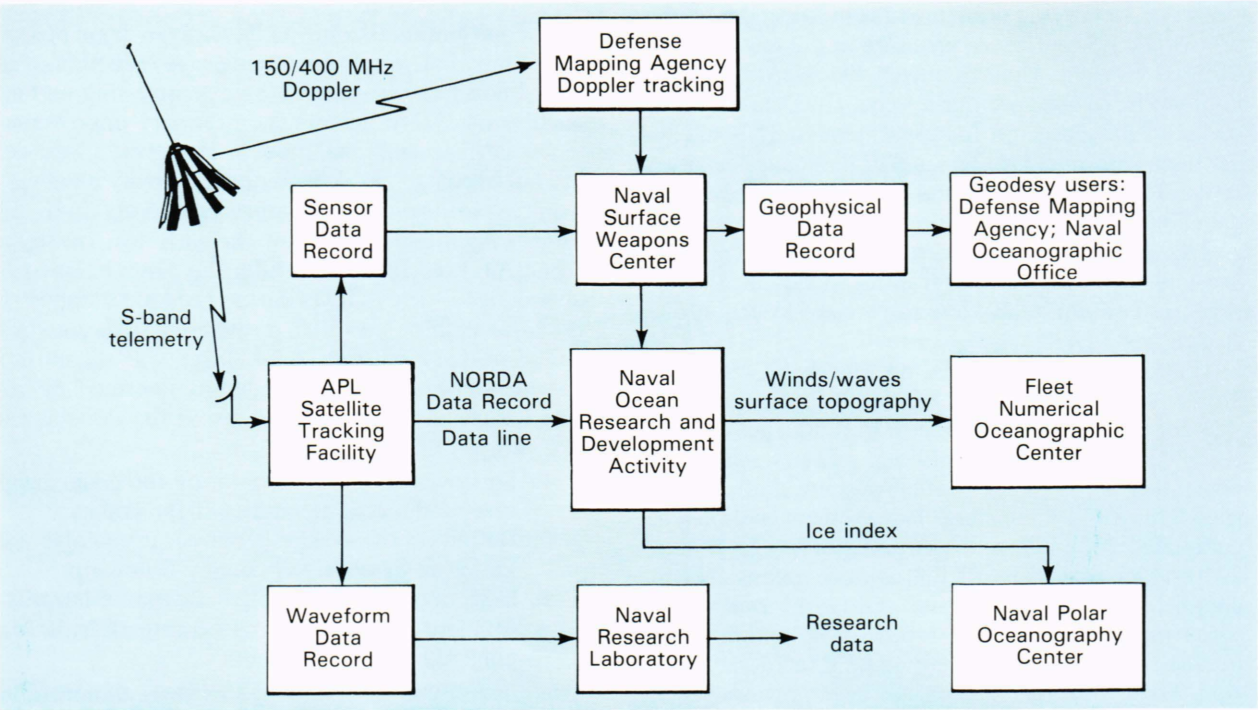

Figure 4—GEOSAT primary mission data flow.

generated in near-real time and transmitted to NORDA over an encrypted data line.

3. Waveform Data Record—an unclassified computer-compatible tape containing the raw waveform samples from the altimeter. The tape is given to the Naval Research Laboratory for ice studies.

GEOSAT Geodesy Determination

The Geophysical Data Record, the primary data set for geodesy determination, is produced at the Naval Surface Weapons Center. First, additional quality control, including land/ice separation, is performed on raw Sensor Data Record data. The precise ephemeris is then fitted to the data, and records with corrections for tides and the environment are added. The article by Smith et al. elsewhere in this issue describes the production of the Geophysical Data Record.

The resulting classified tapes are given to the Naval Oceanographic Office and to the Defense Mapping Agency Aerospace Center for final geodesy processing. The dense 18-month grid of 3-centimeter precision-altimetry data has dramatically improved the Department of Defense global geoid. (See the articles by Van Hee and by Sailor and LeSchack elsewhere in this issue for a discussion of the quality of the data and the final geoid determination.)

GEOSAT Tactical Oceanography

In 1981, the Navy began the GEOSAT Ocean Applications Program to develop a semioperational tactical oceanography capability for Fleet support. The objective was to provide a Sensor Data Record field in near-real time to NORDA. A 9600-baud encrypted telecommunications circuit was installed between the SEL 32 computers at APL and NORDA to support this data requirement. Processing software to produce a NORDA Data Record (essentially a nonquality-controlled Sensor Data Record) at APL was developed, as well as the communications software to support the IBM X.25 circuit protocol at both APL and NORDA. Data have been transmitted routinely over this line since launch.

At NORDA, wind and wave data are extracted from the NORDA Data Record and forwarded in near-real time to the Fleet Numerical Oceanographic Center, Monterey, Calif., for inclusion in numerical analysis models. Twice weekly a mesoscale analysis of a section of the northwest Atlantic Ocean is produced and sent to the Fleet Numerical Oceanographic Center and the Naval Eastern Oceanography Center in Norfolk, Va. Finally, an ice-edge depiction for the Arctic and Antarctic areas is provided each day to the Joint Ice Forecast Center located at the Naval Polar Oceanography Center in Suitland, Md.

The results of analyzing GEOSAT data for tactical oceanographic applications have been encouraging. An extremely good correlation between altitude variations and significant oceanographic features has been verified using National Oceanic and Atmospheric Administration (NOAA) and Geostationary Operational Environmental Satellite infrared imagery. Of particular significance is the altimeter signature of cold-water eddies in the Sargasso Sea, a feature that does not show up in the infrared data. Articles by Lybanon and Crout and by Mitchell et al. in this issue describe the oceanographic processing at NORDA with examples of the products that are generated.

GEOSAT Wind and Wave Research

The altimeter directly measures significant wave height by measuring the range extent of the ocean surface. Wind speed, however, must be inferred from the altimeter's measurement of the backscatter (reflection) coefficient of the surface. The development of the best algorithm to determine wind speed has been an active research goal at the Naval Research Laboratory and at APL. As described by Shuhy et al. and Dobson et al. elsewhere in this issue, a direct comparison between altimeter- and buoy-measured winds is difficult, with errors inherent in the buoy instruments and with both spatial and temporal sampling errors masking the differences between candidate algorithms.

GEOSAT Oceanographic Research

The Northwest Atlantic Regional Energetics Experiment Project. The GEOSAT data are supporting this Navy research, development, test, and evaluation project at NORDA. The project combines GEOSAT altimetry data; infrared data; deep (800-meter) airborne expendable bathythermography surveys; deployed inverted echo sounder and bottom pressure-gauge arrays; and eddy-resolving, primitive-equation numerical modeling to study the dynamics and energetics of mesoscale fluctuations in the Gulf Stream near the New England Seamount Chain. In addition to providing excellent surface truth data for GEOSAT, the project will, for the first time, attempt to correlate surface topography signature and measured subsurface features to provide modeling techniques for oceanographic analyses. The article by Mitchell et al. in this issue describes the project.

NOAA Research at APL. A program sponsored and funded by the NOAA National Geodetic Survey entitled Global Sea Level Variability from GEOSAT Altimetry was approved by the Navy and implemented in late 1985. Under the direction of R. E. Cheney and B. C. Douglas, a classified computer facility was established at APL within existing GEOSAT security guidelines. An access agreement was signed by APL, NOAA, and the Navy, wherein processed Sensor Data Record tapes and precise ephemeris data are given to NOAA along with environmental corrections from the Fleet Numerical Oceanographic Center. A Geophysical Data Record is produced by NOAA, and both crossover differences and sea height variability fields are created. Under the agreement, relevant research papers are cleared by the Navy for open publication. A validation procedure is being developed to make possible the release of crossover-difference data tapes from the 18-month geodesy mission. The article by Cheney et al. in this issue describes this NOAA research effort.

Regional Topography Determination. As antisubmarine warfare grows more sophisticated, it has become critical that the operational commander have an accurate map of local mesoscale oceanography. A. R. Robinson and his colleagues at Harvard have demonstrated that regional models of mesoscale features can be installed on small computers suitable for implementation on major ships. The model accepts input from several environmental data sources including surface temperature maps, available expendable bathythermography data, the topography generated directly by the radar altimeter, etc. The Navy Tactical Environmental Support System, now in its early deployment phase, will implement this concept on major surface ships.

The NOAA Geophysical Data Record produced at APL supports a joint regional topography research effort by Harvard University, NOAA, and APL as described in articles by Calman, Dobson et al., Robinson and Walstad, and Cheney et al. elsewhere in this issue.

NASA Waveform Modeling and Ice Research. An adaptive tracker in the altimeter measures range, leading-edge slope, and automatic gain control level by processing the radar return. Both the measured parameters and the raw radar-return waveform are telemetered to the ground.

The data are being used at NASA to provide better models of the shape of the radar pulse reflected from the ocean surface, thus allowing the design of a more accurate tracker for future altimeters.

The radar signals over ice are more complex than returns over the open ocean. The surface topography of ice sheets can be measured by analyzing the raw return waveforms to correct the range values for leads and lags in the altimeter tracking circuit. NASA research is described in the articles by Hayne and Hancock III and by Zwally et al. in this issue.

THE GEOSAT EXACT REPEAT MISSION

Under the guidance of J. L. Mitchell at NORDA, planning was initiated in early 1983 for an Exact Repeat Mission with an orbit optimized for the operational measurement of fronts and eddies. The accuracy of measuring mesoscale topography at NORDA during the 18-month geodetic mission is limited when the marine geoid is subtracted from the altimeter data to produce mesoscale dynamic topography. This technique is computationally simple, but errors in knowledge of the global geoid directly contaminate the oceanographic measurements. Placing the satellite in an exactly repeating orbit allows long-term averaging to give an accurate local mean surface (along the tracks) that can be subtracted from the data to greatly reduce this source of error.

The Navy Requirement for Tactical Oceanography

For the Exact Repeat Mission, GEOSAT is producing operational measurements of oceanographic features (fronts and eddies) that are critical to strategic and tactical decisions on a continuous, timely, all-weather, global ocean basis. This supports both the operational requirement for environmental data (OR-W0527-OS) and the Joint Chiefs of Staff, validated, Commander-in-Chief Atlantic Fleet Required Operational Capability for Fronts and Eddies (MJCS 204-83).

Ocean Coverage in the Exact Repeat Mission Orbit

The GEOSAT satellite was moved into a 17-day exact repeat orbit with an equatorial ground-track separation of 164 kilometers. The transfer began at the completion of the primary geodesy mission on September 30, 1986, and the system was declared operational in the Exact Repeat Mission by the Navy on November 8, 1986.

In the Gulf Stream, the system provides a grid with 110-kilometer spacing. Along that ground track, the altimeter gives global, all-weather measurements of the surface-elevation change caused by mesoscale oceanography. At these latitudes, however, a single altimeter in orbit produces a grid too widely spaced to allow the measurement of mesoscale features using altimeter data alone. In the operational system, the altimeter data are correlated at NORDA with satellite infrared measurements that map ocean-surface temperature in cloud-free areas. Fortuitously, the satellite ground tracks converge, and altimeter coverage improves at higher latitudes (Fig. 5) where cloud cover is a severe problem for infrared measurements. Three altimeters in orbit provide a stand-alone measurement system with satisfactory coverage at all latitudes.

The ascending nodes of the exact repeat orbit are approximately at $1.05 + n(1.475)°$E longitude, where $n = 0$ to 244. The period of the satellite will be increased approximately once a month to compensate for drag and to maintain the nodes within 1 kilometer of the exact repeat nodes. Three orbit maintenance burns were performed between November 8, 1986, and April 30, 1987, to maintain the repeat within 600 meters (1σ). The exact repeat nodes were chosen to follow the tracks generated by the Seasat spacecraft. Since the Seasat altimeter data were released freely, Exact Repeat Mission data can be distributed without the security restrictions that applied to the geodesy mission. The orbit maneuver and repeat orbit parameters are described in the article by Born et al. elsewhere in this issue.

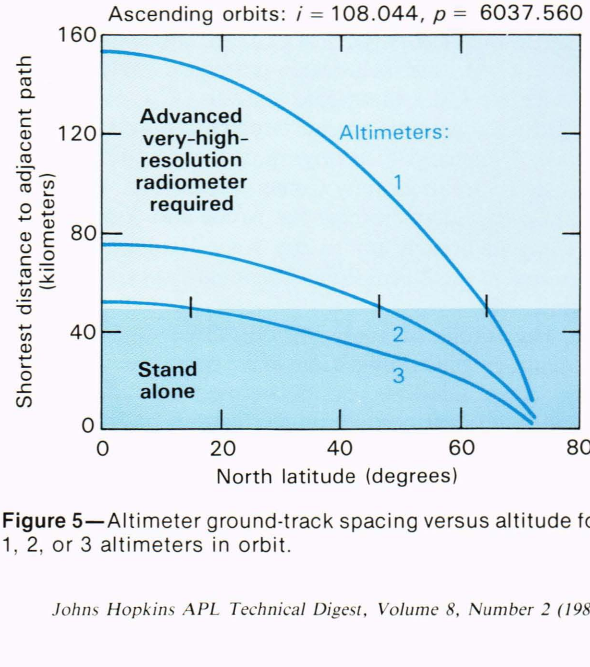

Figure 5—Altimeter ground-track spacing versus altitude for 1, 2, or 3 altimeters in orbit.

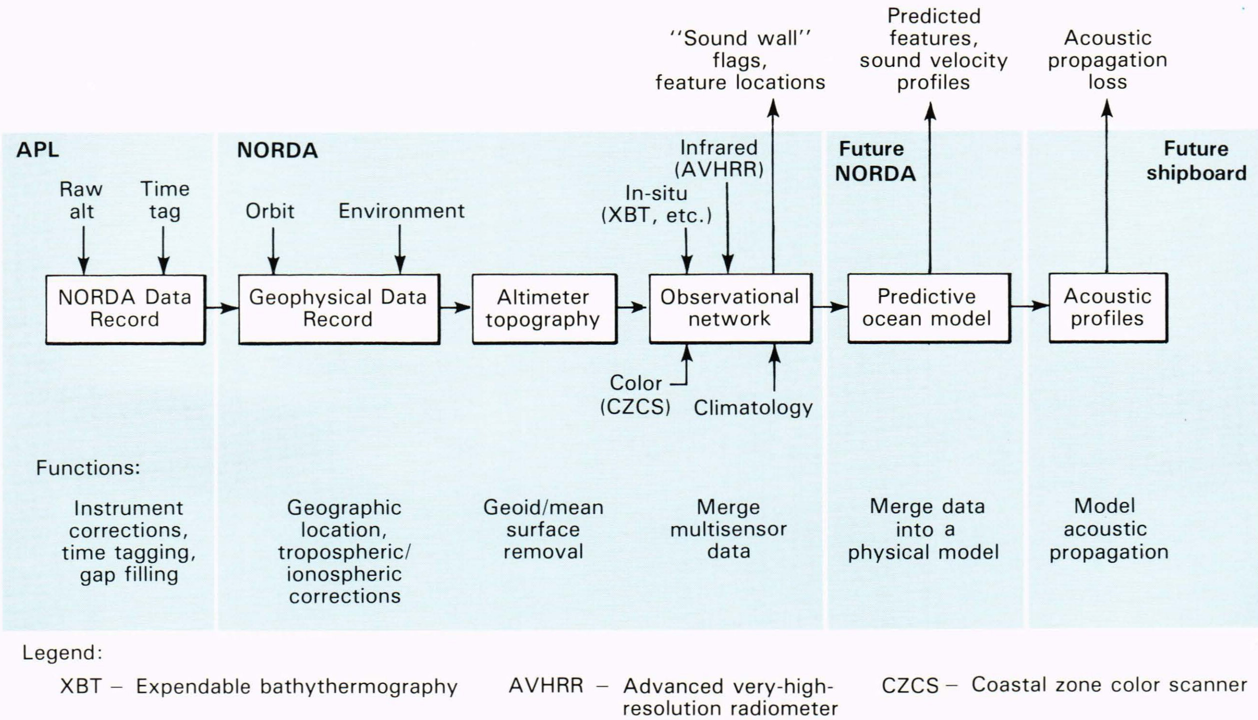

Figure 6—Exact Repeat Mission processing flow.

Exact Repeat Mission Data Products and Orbit Determination

The operational generation and transmission of near-real-time data to NORDA assumes primary importance in the Exact Repeat Mission. Altimeter and timing data are merged and an orderly data set is created at APL (Fig. 6). Atmospheric corrections, orbit merge, and mean surface removal at NORDA produce records of sea-surface heights along the altimeter tracks. The data are merged with other satellite and in-situ data to produce operational maps of feature locations that directly indicate regions of anomalous sonar propagation. The data are also used to initialize and update developmental ocean models that predict the future evolution of oceanographic features and that map underwater sound velocity fields. The ultimate goal of the system is the production of global environmental data needed to drive range-dependent sonar models.

Orbit parameters for the operational system are generated by the Navy Astronautics Group using a GEM-10 gravity model and Doppler tracking data from the four Transit OPNET tracking stations. Orbital data are given to APL for orbit maintenance, to NORDA for geolocation of the altimeter data, and to NOAA for inclusion on the Geophysical Data Record tapes.

The distribution network was extended for the Exact Repeat Mission to provide data to unclassified users. Under an agreement reached with the Navy and with APL, NOAA has assumed responsibility for generating the unclassified data sets. A copy of each Sensor Data Record is transmitted to a NOAA processing facility in Rockville, Md. The raw data are merged with the ephemeris data supplied by the Navy Astronautics Group and correction fields are added for tides, wet and dry troposphere, and ionosphere to yield Geophysical Data Records. Completed records are sent to the NOAA National Environmental Satellite Data and Information Services in Washington, D.C., where they are made available to the public. Detailed information on the data format and content can be obtained from R. E. Cheney, Mail Code N/CG11, National Ocean Service, NOAA, Rockville, Md. 20852.

NOTE

[1]GEOSAT is a research and development program under the Chief of Naval Operations Satellite Division (OP-943), with management and scientific guidance given by the Space and Naval Warfare Systems Command, Office of Naval Research, Naval Surface Weapons Center, Naval Oceanographic Office, Naval Ocean Research and Development Activity, Navy Astronautics Group, Naval Research Laboratory, and Defense Mapping Agency.

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