68p.

JPL PUBLICATION 86-18

CR

IN - 28830

Science Opportunities From the Topex/Poseidon Mission

R. Stewart
L.-L. Fu
Jet Propulsion Laboratory

M. Lefebvre
Centre Spatial de Toulouse

(NASA-CR-179752) SCIENCE OPPORTUNITIES FROM THE TOPEX/POSEIDON MISSION (Jet Propulsion Lab.) 68 p CSCL 08C

N87-10671

Unclas
G3/48 44225

July 15, 1986

NASA
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL PUBLICATION 86-18

Science Opportunities From the Topex/Poseidon Mission

R. Stewart
L.-L. Fu
Jet Propulsion Laboratory

M. Lefebvre
Centre Spatial de Toulouse

July 15, 1986

NASA
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

The research described in this publication was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

NASA
National Aeronautics and
Space Administration

Washington, D.C.
20546

Attn of: EE

Dear Colleague:

The first oceanographic instrument in space was a microwave sensor that flew aboard NASA's Skylab in 1972. Since that time, ocean-related sensors have flown aboard several U.S. satellites, including Nimbus-7 and Seasat--the first dedicated oceanographic satellite--launched in 1978. The NASA Seasat altimeter clearly demonstrated that spaceborne microwave altimeters were capable of obtaining global measurements of ocean topography with sufficient precision and accuracy to be useful for oceanographic studies.

Looking to the future, both NASA and the French Centre National d'Etudes Spatiales (CNES), in cooperation with other national partners, have been planning the coordinated TOPEX/POSEIDON dedicated altimeter satellite mission for observing the oceans. In concert with the TOPEX/POSEIDON mission, NASA also has plans for a series of spaceflight activities designed to further our understanding of ocean circulation, air-sea interactions, and the biological processes taking place in the upper ocean. This series--the NASA Scatterometer (NSCAT) to fly aboard the U.S. Navy Remote Ocean Sensing System (N-ROSS) satellite, the NASA/CNES TOPEX/POSEIDON altimeter mission, and a color scanner for a platform of opportunity--will also contribute to the Global Change, the International Geosphere/Biosphere, and World Climate Research Programs.

I would like to take this opportunity to inform you that the TOPEX/POSEIDON mission has been proposed by NASA for a new start in FY 87. The TOPEX/POSEIDON measurements of surface topography of the global oceans have the potential to enhance our understanding of the oceanic circulation, as well as the ocean's role in climate variability. In addition, these measurements will provide information that will allow studies of tides, sea state, and marine geophysics.

This Science Opportunities Document describes the capabilities of the TOPEX/POSEIDON instruments and outlines various types of experiments that could be performed utilizing TOPEX/POSEIDON data. I hope that this document will aid you and your colleagues in preparing to exploit the potential offered by the jointly sponsored NASA/CNES TOPEX/POSEIDON mission, and I invite you to share in the scientific planning and execution of this exciting project.

Sincerely,

S. G. Tilford

S. G. Tilford, Director
Earth Science and Applications Division
Office of Space Science and Applications

Abstract

The U.S. National Aeronautics and Space Administration (NASA) and the French Centre National d'Etudes Spatiales (CNES) propose to conduct a Topex/Poseidon mission for studying the global ocean circulation from space. The mission will use the techniques of satellite altimetry to make precise and accurate measurements of sea level for several years. The measurements will then be used by Principal Investigators (selected by NASA and CNES) and by the wider oceanographic community working closely with large international programs for observing the Earth, on studies leading to an improved understanding of global ocean dynamics and the interaction of the ocean with other processes influencing life on Earth.

The major elements of the mission include a satellite carrying an altimetric system for measuring the height of the satellite above the sea surface; a precision orbit determination system for referring the altimetric measurements to geodetic coordinates; a data analysis and distribution system for processing the satellite data, verifying their accuracy, and making them available to the scientific community; and a Principal Investigator program for scientific studies based on the satellite observations.

This document describes first of all the satellite, its sensors, its orbit, the data analysis system, and plans for verification and distribution of the data. It then discusses the expected accuracy of the satellite's measurements and their usefulness to oceanographic, geophysical, and other scientific studies. Finally, it outlines the relationship of the Topex/Poseidon mission to other large programs, including the World Climate Research Program, the U.S. Navy's Remote Ocean Sensing System satellite program, and the European Space Agency's ERS-1 satellite program.

Acknowledgment

A substantial portion of Section IV on the ocean topography experiment was adapted from the report *Satellite Altimetric Measurements of the Ocean: Report of the TOPEX Science Working Group,* a group chaired by Professor Carl Wunsch.

Contents

Figures

Figures (contd)

Figures (contd)

Tables

Section I
Introduction

The movement of water in the ocean influences human life in a variety of ways. On the Earth, contrasts in climate between the poles and equator are greatly ameliorated by the presence of the ocean because of its large heat capacity and its contribution to the movement of heat from the equator to the poles. Much of the weather we experience is spawned over the ocean through complex air-sea transfer processes. The important global fishing grounds are limited to small geographical areas dominated by special oceanic flows, and the movement of chemical tracers and pollutants in the sea is and will be important. For example, the rate at which the burning of fossil fuel causes the temperature of the air to rise is determined to a large extent by the rate at which the ocean will be able to absorb the CO_2 and by the rate at which the ocean warms due to increased atmospheric heating (National Research Council, 1979a, 1983a).

Yet much about the ocean is poorly understood, largely because the ocean is so difficult to observe. It is a global fluid, and like the atmosphere it appears to have both climate and weather. But unlike meteorologists, oceanographers have no global observation system, only fragmentary and ephemeral regional observation systems based primarily on measurements from ships.

Given the global nature of the sampling problem, only satellite systems have the potential for providing the data necessary to understand the oceans as a whole. Two types of satellite measurements are used to observe the sea surface: passive and active. The passive measurements are commonly used to measure the oceanic color, temperature, and ice cover and atmospheric water vapor; and they can be used to compute the fluxes of latent heat at the sea surface. Active measurements are used to measure the roughness and topography of the sea surface, which provide information about wave height, wind speed and direction, surface geostrophic currents, and tides.

Active measurements are made by a variety of special radars. Two types are particularly useful: scatterometers and altimeters. Scatterometers illuminate the sea surface at nonvertical angles and then measure the intensity of the returned signal. The intensity is directly related to the roughness of the sea surface, and the measurements of intensity are used to calculate surface wind velocity. Altimeters illuminate the sea surface at the nadir using a short pulse of electromagnetic radiation and then measure the intensity, arrival time, and structure of the reflected pulse. The intensity and structure of the pulse are used to observe wind speed and wave height, respectively. The arrival time of the pulse gives the height of the spacecraft above the sea surface. If the spacecraft also carries systems to measure its height relative to the center of the Earth using techniques of precision orbit determination, then the difference of the two heights gives the height of the sea surface in coordinates relative to the center of the Earth (Greenwood, et al., 1969; Stewart, 1985, Ch. 14). This height is called sea level.

Sea level is determined mostly by gravity (Fig. 1). If the ocean were at rest, sea level would be a surface of constant gravitational potential, the geoid. Surface geostrophic currents, tides, and other dynamical processes in the ocean cause sea level to deviate from the geoid. These deviations are the oceanic topography. Although altimetric satellites measure sea level, variations in sea level as a function of time observed by an altimeter must be due to temporal variability of the topography. Hence, altimeters also measure topography. The following discussions tend to use *sea level* and *topography* interchangeably, but the correct meaning will be clear from the context.

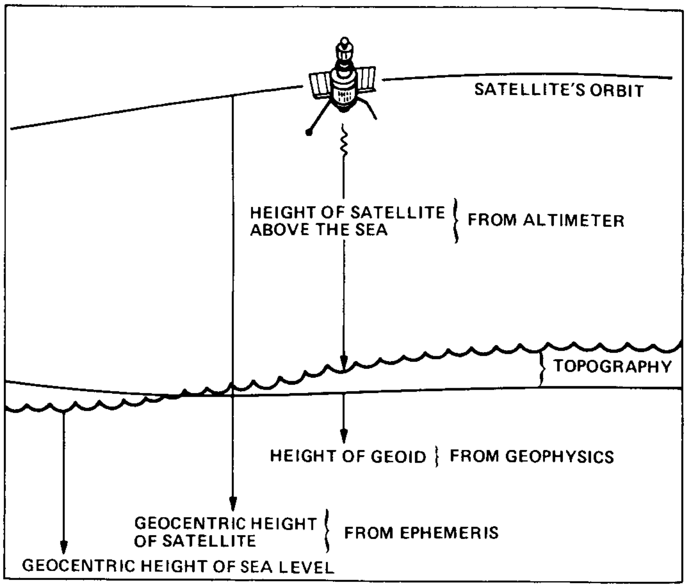

Fig. 1. A satellite altimeter measures the height of the satellite above the sea surface. When this is subtracted from the height of the satellite's orbit, the difference is sea level. Variations in sea level are due to gravity and ocean currents.

The usefulness of satellite altimetry for measuring sea level and the ocean topography has been demonstrated by a series of altimeters of increasing accuracy and precision flown on Skylab, Geos-3, Seasat, and Geosat (Mather, et al., 1980; Cheney and Marsh, 1981a; Menard, 1983; Fu, 1983b). Data from Seasat have been especially useful and have allowed oceanographers to map the surface topography of the ocean and the oceanic geoid in unprecedented detail.

Altimeter measurements of sea level, and hence topography, are particularly useful for several reasons. First the altimeter observations, together with theories of ocean dynamics, show that the topography of the ocean is directly related to surface geostrophic currents, which can be directly related to processes occurring at depth in the ocean. Surface geostrophic currents result from a balance between pressure gradients and the Coriolis force due to the current, and they are equivalent to the circulation around highs and lows in the atmosphere (see Section IV.A.1). Unlike other oceanographic variables measured from space (such as sea-surface temperature or color), sea level is a dynamical rather than a thermodynamical, or passive, variable and is thus directly related to the governing equations for the ocean as a whole. Second, unlike many other satellite measurements, radar altimetry is not limited to cloud-free periods. And finally, the Geos-3, Seasat and Geosat results have demonstrated that satellite altimeters can measure topography globally with the accuracies required for studies of ocean dynamics and circulation.

The usefulness of satellite altimeters has led to proposals to place new altimeters in orbit. The National Aeronautics and Space Administration (NASA) has developed over the past six years an Ocean Topography Experiment, Topex, to measure oceanic topography using an advanced altimeter on a compact satellite with an accurately known orbit. At the same time, the French Centre National d'Etudes Spatiales (CNES) has been studying the possibility of measuring the ocean topography using a system that includes a solid-state altimeter, a dedicated tracking system, and a radiometer to be flown on one of the Spot series of satellites. The similarity of the two projects, the interest in joint French-American cooperation in space as well as in oceanography, and the favorable results of a joint study of the technical issues involved in a joint mission led to a decision by both space agencies to combine the two projects into the Topex/Poseidon mission.

The combined Topex/Poseidon mission is designed to make substantial contributions to our understanding of global ocean dynamics by making precise and accurate observations of the oceanic topography for three to five years using radar altimeters on a well-tracked satellite.

When combined with accurate geoid models, with global measurements of the thermodynamic (solar insolation and evaporation) forcing and wind stress at the sea surface, and with direct observations or models of the deeper circulation, the Topex/Poseidon observations of sea level will lead to a full three-dimensional view of the oceanic general circulation. The additional information necessary to complement the Topex/Poseidon data will be available from a variety of sources: Accurate geoids will be obtained from planned NASA and foreign space missions dedicated to the measurement of the Earth's gravity field; satellite scatterometers will be used to measure surface winds; new methods for analyzing data from meteorological satellites are providing calculations of the incoming solar radiation and latent heat flux at the sea surface; trajectories of drifting buoys deployed at the surface and at intermediate levels measure currents at these depths in the ocean; and measurements of the distribution of transient tracers define the movement of the water in the deepest layers. Finally, new supercomputers are making possible the development and use of improved models of the circulation of the ocean and atmosphere, including models that couple the two systems and future models that could eventually incorporate the full set of global measurements that will be available from spaceborne instruments.

The importance of the global problems and the development of new techniques to observe and analyze the oceans and atmosphere as a whole have led to proposals for several large programs to study the planet Earth. These include the International Geosphere-Biosphere Program, the Global

Change Program, and the World Climate Research Program (National Research Council, 1983b; World Meteorological Organization, 1985). Although each has different emphasis, all require studies of the ocean circulation.

Of the three, the planning for the World Climate Research Program is most advanced. This program, under the auspices of the World Meteorological Organization, the Intergovernmental Oceanographic Commission, and the International Council of Scientific Unions, includes several large-scale oceanographic experiments to study the general circulation of the ocean, its response to external forcing, and its interaction with the atmosphere in order to understand the role of the ocean in climate (World Meteorological Organization, 1983, 1985). The Topex/Poseidon mission will be an essential contribution to the World Climate Research Program and will benefit from the extensive surface and subsurface observations that will be made by the program. In addition, the U.S. Navy and European Space Agency both plan to fly oceanographic satellites during the Topex/Poseidon mission. These are the Navy's Remote Ocean Sensing System (NROSS) satellite and the European Space Agency's ERS-1 satellite. Both will carry scatterometers to measure wind speed and direction, and the ERS-1 satellite will carry an altimeter that will complement the measurements made by Topex/Poseidon. Other instruments will provide additional, useful data for the World Climate Research Program.

Finally, any satellite mission produces more information than that for which it was designed. So it is with Topex/Poseidon. The Topex/Poseidon altimeters will provide data that might be used to measure, with varying accuracies, wind speeds, wave height, rainfall, sea ice boundaries, the level of plains on land, and other phenomena of interest to Earth scientists. In addition, auxiliary measurements necessary for reducing errors in the satellite altimetry will produce useful information on water vapor in the troposphere, free electrons in the ionosphere, and the gravity field of Earth.

This document outlines the satellite system, the measurements that will be made by the satellite, the accuracy of the measurements, the plans to process, verify, and distribute data, the type of scientific studies that might be conducted using these data, and the relationships between these scientific studies and others being planned by the oceanographic community. Some possible oceanographic studies based on altimeter data were discussed in *Satellite Altimetric Measurements of the Ocean: The Report of the Topex Science Working Group* (NASA, 1981) and in *Poseidon* (CNES, 1983). Both served as guides for the preparation of this document. The descriptions of potential experiments given here are not comprehensive, so potential investigators are urged to evaluate the usefulness of Topex/Poseidon data for their own specific oceanographic studies.

Section II
Topex/Poseidon Mission

Knowing that accurate measurements of sea level contain information about surface currents, tides, and waves and knowing that sea level can be measured by satellites, the Topex and Poseidon projects have worked together to design a specific altimetric satellite mission that will increase substantially our understanding of global ocean dynamics by making precise and accurate observations of sea level for several years. These observations will then be used by Principal Investigators (selected by NASA and CNES) and by the wider oceanographic community working closely with large international programs for observing the Earth on studies leading to an improved understanding of global ocean dynamics and the interaction of the ocean with other global processes influencing life on Earth.

The specific goals of the Topex/Poseidon mission are to do the following:

(1) Measure sea level in a way that allows the study of ocean dynamics, including the calculation of the mean and variable surface geostrophic currents and the tides of the world's oceans.

(2) Process, verify, and distribute the data in a timely manner, together with other geophysical data, to science investigators.

(3) Lay the foundation for a continuing program to provide long-term observations of the oceanic circulation and its variability.

The Topex/Poseidon mission that has been designed to meet these goals includes an altimetric system to measure the height of the satellite above the sea surface; a precision-orbit determination system to refer satellite measurements to geodetic coordinates; a data analysis and distribution system to process the satellite data, verify their accuracy, and make them available to the scientific community; and a Principal Investigator program to use the observations of oceanic topography to increase substantially our understanding of global ocean dynamics useful for a wide range of environmental studies. This section describes the satellite, its sensors, its orbit, the data analysis system, and plans for the verification and distribution of data. Subsequent sections consider the accuracy of the satellite's measurements and their usefulness to oceanographic, geophysical, and other scientific studies.

Although the details of the mission described here are current as of the printing of this document, minor changes may be made in the final design and fabrication of the satellite, its sensors, and the system to process and verify the satellite data. Some of these changes could significantly influence work proposed by the Principal Investigators, e.g., by changing the repeat period of the satellite's orbit. The Principal Investigators selected by NASA and CNES will be expected to contribute to the work of a Science Working Team, the purpose of which is to provide, among other tasks, general scientific advice on the Topex/Poseidon mission, and help in writing a Science Plan that will coordinate the work of the Principal Investigators.

A. Requirements and Capabilities

The Topex/Poseidon mission was derived from requirements for a satellite altimetric system established by the Topex Science Working Group (NASA, 1981) and by the Poseidon report to CNES (1983). These requirements were further refined and reviewed during the conceptual design (Phase A) and definition studies (Phase B) conducted by the Jet Propulsion Laboratory and the Toulouse Space Center.

As a result of that work, the mission is planned to have the following characteristics.

1. Satellite

The satellite and its major subsystems will be purchased by NASA from U.S. industry. The satellite will be a modification of an existing design from one of three contractors who completed Phase B studies. The three companies are the Fairchild Space Company, RCA Astro-Electronics Company, and Rockwell International Satellite Systems Division.

To make possible an accurate calculation of the satellite's orbit, the forces acting on the satellite must be well known. Hence, the satellite must be compact, must have surfaces of known and predictable reflectivity, thermal emissivity and orientation, must have a well-known center of gravity throughout the mission, and must have a minimum amount of outgassing to reduce nongravitational forces acting on the satellite.

The satellite will be designed for launch by the Ariane, and for retrieval (if necessary) by the shuttle (see Section II.A.6 and 10).

2. Instruments

The Topex/Poseidon satellite will carry both NASA and CNES instruments (Table 1 and Section II.B). The NASA instruments include (1) an advanced dual-frequency radar altimeter to measure the height of the satellite above the sea surface and to correct this measurement for the effect of free electrons in the ionosphere; (2) a three-frequency microwave radiometer to make observations necessary to correct the altimeter measurements for the effect of tropospheric water vapor; (3) a Tranet beacon to provide the primary tracking of the satellite; (4) a laser retroreflector assembly to allow ground-based lasers to verify the altimeter measurements of height and to provide supplemental precision tracking of the satellite; and (5) a Global Positioning Satellite receiver to provide data useful for testing new methods for accurately tracking the satellite's position. The CNES instruments include a single-frequency solid-state altimeter and a radiometric tracking system using a one-way Doppler system called Doris that receives signals transmitted by beacons on the ground.

The altimeter measurements of height, when combined with an accurate ephemeris (a table of positions of the satel-

Table 1. Topex/Poseidon instruments

System	Instrument	Purpose	Frequency	Bandwidth
Topex	Altimeter	Measures height of satellite above the sea, wind speed, wave height, and ionospheric correction	5.3 GHz 13.6 GHz	320 MHz 320 MHz
	Radiometer	Measures water vapor along the path viewed by the altimeter, which is used to correct the altimeter for pulse delay due to water vapor	18.0 GHz 21.0 GHz 37.0 GHz	220 MHz 220 MHz 220 MHz
	Tranet Beacon	Provides Doppler signal for Tranet ground stations for precision orbit determination	400.0 MHz 150.0 MHz	– –
	Global Positioning Satellite Receiver*	Provides a new tracking data type (range differences) for precision orbit determination	1227.6 MHz 1575.4 MHz	– –
	Laser Retroreflector	Used with ground-based lasers to calibrate and verify altimeter measurements of height	–	–
Poseidon	Altimeter*	Measures height of satellite above the sea, wind speed, and wave height	13.65 GHz	330 MHz
	Doris	Receives signals from ground stations for satellite tracking, gravity field measurements, and ionospheric correction for altimeter	401.25 MHz 2036.25 MHz	150 KHz 50 KHz

*Experimental Instruments

lite in its orbit), provide the measurement of sea level (Fig. 1). The redundant altimeter and tracking systems have two important advantages. Redundancy increases the reliability of the mission, and the comparison of different measurements of the same variable made by different instruments leads to a much improved understanding of the errors in the measurements.

3. Accuracy of Sea-Level Measurements

Each measurement of sea level will have a precision of ±2.0 cm and an accuracy of ±14 cm (1 standard deviation) for typical oceanic conditions, with small geographically correlated errors. In this context, precision is the ability to determine changes in sea level over distances of 20 km, and accuracy is the uncertainty of each measurement of sea level when expressed in geocentric coordinates. Detecting changes in sea level over distances greater than 20 km depends on the wavelength of the errors that contribute to the inaccuracy of the measurements. One measure of the distance over which errors become important is the decorrelation distance of each source of error. Thus, for example, a process that produces an error with a decorrelation distance of 1000 km will contribute little to measurements of changes in sea level over distances of much less than 1000 km. The primary sources of error in Topex/Poseidon measurements of sea level and a rough estimate of their decorrelation distance are summarized in Table 2. The various entries in the table are discussed further in the following sections of this document.

4. Sampling Strategy

Sea level will be measured along a fixed grid of subsatellite tracks such that it will be possible to investigate and minimize the spatial and temporal aliases of surface geostrophic currents and to minimize the influence of the geoid on measurements of the time-varying topography. Present plans call for the satellite to measure sea level at least every 20 km along a fixed grid of subsatellite tracks that repeat within ±1 km every ten days, although the repetition period may be changed to any value between three and twenty days.

5. Tidal Aliases

Sea level will be measured such that tidal signals will not be aliased into semiannual, annual, or zero frequencies (which influences the calculation of the permanent circulation) or frequencies close to these.

6. Coverage and Duration

Sea level will be measured for a minimum of three years, with the potential to extend this period for an additional two years. The grid of subsatellite tracks will extend in latitude at least as far south as the southern limit of the Drake Passage, which is 62 deg, and the subsatellite tracks that comprise the grid will cross at sufficiently large angles that the two orthogonal components of surface slope can be determined with comparable accuracy.

Table 2. Error budget for Topex/Poseidon measurements of sea level

Error Source	Standard Deviation of Uncertainty, cm	Decorrelation Distance, km
Altimeter		
Instrument noise	2.0	20
Bias drift	2.0	(Many days)
Media		
EM bias	2.0	20-1000
Skewness	1.0	20-1000
Troposphere, dry	0.7	1,000
Troposphere, wet	1.2	50
Ionosphere	1.3 (2.0*)	20
Orbit		
Atmospheric drag	1.0	>10,000
Solar radiation	1.0	10,000
Earth radiation	<1.0	10,000
GM	2.0	10,000
Gravity	10.0	10,000
Earth and ocean tides	1.0	10,000
Station and satellite clock	1.0	10,000
Troposphere	1.0	10,000
Station location	5.0	10,000
Higher order ionosphere	5.0 (1.0†)	10,000
RSS Absolute Error	13.3	

Note: Major assumptions are listed below:

1. Dual-frequency altimeter
2. Dual-frequency radiometer
3. Upgraded Tranet tracking system, 40 stations
4. Altimeter data averaged over 3 s
5. $H_{1/3}$ = 2 m, wave skewness = 0.1
6. Tabular corrections based on limited waveform-tracker comparisons
7. 1300-km altitude
8. No anomalous data, no rain
9. Improved gravity model (by a factor of two over existing models)
10. ±3-mbar surface pressure from weather charts
11. 100-μs spacecraft clock

*For the one-frequency Poseidon altimeter; inferred from models using data from Doris.
†From Doris tracking data

The NASA altimeter will provide the primary observations of sea level, and the CNES altimeter will demonstrate the usefulness of a new class of altimeters that could fly on future spacecraft. The two altimeters will share a common antenna and cannot operate simultaneously. The NASA altimeter will operate 95% of the time on a schedule to be negotiated by NASA and CNES with the agreement of the Topex/Poseidon Principal Investigators. The CNES altimeter will operate for the remaining 5% of the time. Present plans call for the CNES altimeter to operate for one full day out of twenty. Data from the altimeter will be incorporated into the geophysical data records after evaluation of the data (see Section II.A.9).

During the primary altimeter operating periods, at least 90% of all global oceanic data that could be acquired by the spacecraft over a three-year period will be acquired, with no systematic gaps in coverage. The intent is to collect data continuously, but small amounts of data will be lost during adjustments of the satellite's orbit, during tests of the altimeter's performance, and during various other such events.

Although the schedule for the mission is not yet fully established, present plans call for the collection of data to begin in mid 1991 after the launch of the Topex/Poseidon satellite from Kourou, French Guiana, by an Ariane 4 launch vehicle. The spacecraft will operate in a nearly circular observational orbit. For purposes of planning the mission, the orbit is assumed to be at an altitude of 1335 km and an inclination of 63.1 deg (see Section II.C). This orbit lays down a dense grid of subsatellite tracks between 63.1 deg north and south latitudes (Figs. 2 and 3). The constraints leading to the selection of this orbit are discussed in Section II.C.

7. Orbit Maintenance

The orbit of the satellite will slowly decay due to air drag, and it will have long-period variability due to the inhomogeneous gravity field of Earth, solar radiation pressure, and smaller forces. Periodic maneuvers will be required to keep the satellite in the observational orbit. The frequency of maneuvers will depend primarily on the solar flux as it affects the Earth's atmosphere, and it is expected to be one maneuver (or series of maneuvers) every 40 to 200 days. During the maneuvers, altimeter data will not be useful for periods of typically 2 to 6 hours.

8. Phases of the Mission

The first thirty days after the satellite is launched into the observational orbit will be used for assessing the performance of the satellite, its subsystems, and payload. During this period only a very limited amount of data will be available from the instruments. This will be the engineering assessment phase of the mission.

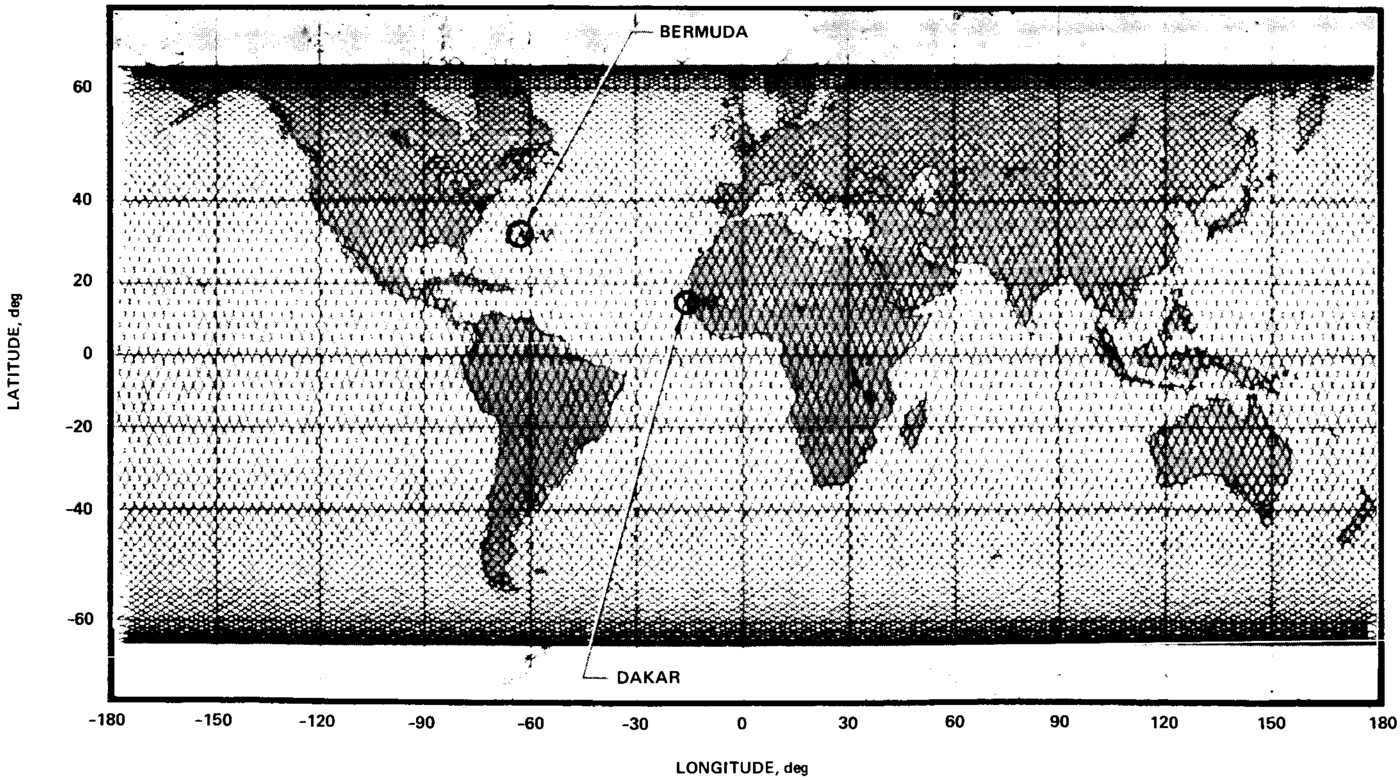

Fig. 2. The ground track traced out by a satellite at an altitude of 1333.8 km and with an orbital inclination of 63.1 deg during a 10-day period of an exactly repeating 10-day cycle

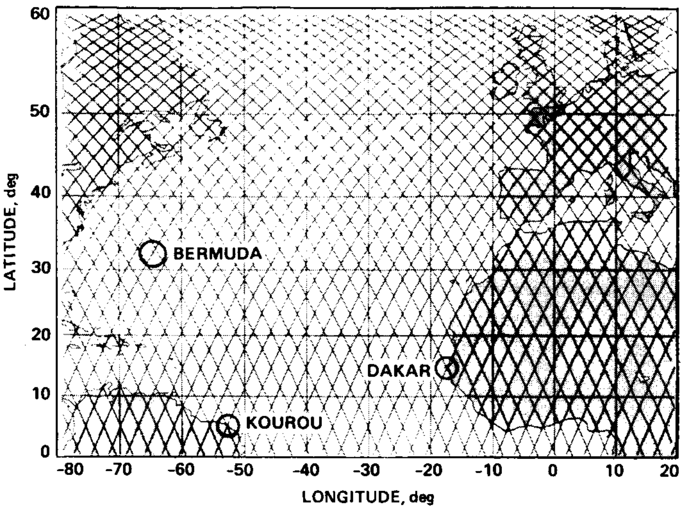

Fig. 3. The ground track traced out by a satellite over the northwestern Atlantic at an altitude of 1333.8 km and with an orbital inclination of 63.1 deg during a 10-day period of an exactly repeating 10-day cycle

The verification and calibration of scientific data from the satellite will begin during the engineering assessment and will continue for up to six months after launch (cf. Section II.D.3). During this period uncalibrated and unverified data will be collected and made available to the Principal Investigators and to those contributing to the verification of the data. This will be the verification phase of the mission.

The observational phase of the mission will begin approximately six months after launch and will continue until the end of the mission. Verification will continue at a low level through this period to ensure the quality of the data. Verified and calibrated data will be produced and distributed during this phase, including data collected during the first six months of the mission.

9. Data Reduction and Distribution

A system to process and distribute data to the Principal Investigators will be tested, documented, and in operation at the time of launch. At least 90% of the data acquired by the spacecraft will be processed and made available for scientific investigations, with no systematic gaps. Again, the intent is to process all data, but some data will be lost due to transmission errors, tape recorder problems, or errors in data handling. Overall, 81% of the oceanic data that could be acquired by the spacecraft will be acquired, processed, and delivered to the scientific community.

NASA and CNES will each process data from their respective instruments and will then exchange processed data. These data will be placed in national archives for further distribution to the scientific community. Plans for the data distribution system are not yet complete, but Principal Investigators selected by NASA should expect to receive data from the NASA Ocean Data System, and investigators selected by CNES should expect to receive data from the French AVISO (Analysis, Validation, Interpretation of Satellite Oceanographic Data) system. Both systems will provide access to data via on-line data management systems. The Principal Investigators will further process the Topex/Poseidon data and will conduct oceanographic or geophysical investigations based on these data.

In exchange for access to Topex/Poseidon data, NASA Principal Investigators are required to publish their findings in the open scientific literature and to make available to national archives the results of their investigations together with annotated and documented copies of their analyzed data. In particular, Principal Investigators will contribute to a Project Data Management Plan that documents plans for data analysis, dissemination of results, and making analyzed data and supporting documentation available to the scientific community through national data archives. The plan will be approved by the Topex and Poseidon Project Managers with the concurrence of the Topex and Poseidon Project Scientists and the Director of the U.S. National Space Science Data Center. Principal Investigators must agree to the terms of the plan prior to receiving Topex/Poseidon data.

During the verification phase of the mission, uncalibrated and unverified interim geophysical data will be available to a verification team (see Section II.D.3) and Principal Investigators within five days after the receipt of satellite data by the project. Both groups are expected to work together on an assessment of the accuracy of the geophysical data.

During the observational phase, verified and calibrated geophysical data will be available to Principal Investigators within six months of the receipt of data by the project. The primary cause of the delay is the time required for verifying the geophysical data and computing an accurate ephemeris. The delay is expected to shrink as the backlog of data acquired during the verification period is processed and as the calculation of the accurate ephemeris is streamlined.

To help plan oceanographic experiments, small amounts of interim geophysical data will also be available within five days of data acquisition, during the observational phase of the mission. These data will lack only an accurate ephemeris. In addition, altimeter observations of wave height and wind speed will be processed and transmitted to the U.S. Navy's Fleet Numerical Oceanographic Center (FNOC) within four hours of the satellite's observations.

Geophysical data records will have a format similar to the Seasat altimeter records; and they will consist primarily of satellite measurements of sea level, including all corrections applied to the data, plus the precise ephemeris of the satellite, the altimeter measurements of wave height, wind speed, and ionospheric electron content, and the microwave radiometer observations of brightness temperature at three radio frequencies plus the derived value of tropospheric water vapor (Table 3). The records will also include the best available values for the height of the tides and geoid. All measurements will be appended with the latitude, longitude, and time of the observation and will be located along the grid of subsatellite tracks. The measurements will not be interpolated to a uniform grid of points in latitude and longitude. All data used to calculate the final data will be archived.

10. Retrievability

The spacecraft will be retrievable by the U.S. Space Transportation System (the shuttle) in the event of a major malfunction that would render the satellite unable to accomplish its scientific mission. The satellite will carry enough propellant to return from the observational orbit at an altitude of 1334 km to the shuttle altitude of 315 km and will carry fixtures to enable the satellite to be captured and stowed on the shuttle.

Table 3. Topex/Poseidon geophysical measurements

Instrument	Variable	Footprint, km × km	Accuracy (Precision)
Topex Altimeter	Satellite height	3 × 20*	(±2 cm)†
	Wave height	3 × 20*	0.5 m or ±10%
	Electron content	3 × 20*	$\pm 3 \times 10^{16}$ e/m^2
	Radar reflectivity	3 × 20*	±0.25 dB
	Wind speed	3 × 20*	±2 m/s**
Altimeter and Tracking Systems	Sea level	3 × 20*	±14 cm‡
Poseidon Altimeter	Satellite height	3 × 20*	(±4 cm)
	Wave height	3 × 20*	0.5 m or ±10%
	Wind speed	3 × 20*	±2 m/s
Microwave Radiometer	Water vapor	35 × 35	±2 kg/m^2
	Path length	35 × 35	±1.2 cm
Laser Retroreflector	Laser range	--	±5 cm

*Depends on sea state.

†For 2-m significant wave height.

‡See Table 2 for assumptions.

**Based on specified accuracy for radar reflectivity and assuming the Chelton and McCabe (1985) relationship for wind speed.

B. Sensors

The primary Topex/Poseidon instruments are derived, in the main, from similar instruments or systems that have flown on previous space missions. The Topex altimeter is based on the design of the Seasat and Geosat altimeters; the microwave radiometer will use subsystems from the scanning multichannel microwave radiometer flown on Seasat and Nimbus-7; and the Tranet beacon and laser retroreflector are based on designs used on Seasat and other satellites. The Global Positioning System demonstration receiver will be a space-qualified instrument partially derived from existing Global Positioning System receivers. The Doris receiver, which will be flown on Spot-2 in 1988, will be based on experience gained from the Argos system now operating on the NOAA polar-orbiting meterological satellites. Only the CNES altimeter is an entirely new design. To reduce risk in the development of these instruments, prototype models of the Topex and Poseidon altimeters and the Doris receiver and beacons have been built.

This conservative approach for providing Topex/Poseidon instruments has two advantages: (1) It increases the reliability of the instruments; and (2) it allows geophysical algorithms derived for earlier missions to be used with only minor modifications, respectively increasing the accuracy of the observations and decreasing the time and expense necessary to process and verify data from the instruments.

1. NASA Dual-Frequency Altimeter

The NASA altimeter will provide the primary measurement of the height of the satellite above the sea surface, being designed to measure the height with a precision of ±2.0 cm when the observations are averaged over 3 s. The altimeter is based on earlier instruments flown on Skylab, Geos-3, Seasat, and Geosat (Table 4) but includes a second frequency to measure errors due to free electrons in the ionosphere. Two independent altimeters operating at K_u (13.6 GHz) and C (5.3 GHz) bands will each measure the height of the sensor above the ocean surface (Table 5). Because the pulse delay due to free electrons is inversely proportional to the square of the radar frequency, the difference in the heights measured by the two channels will yield propagation delay due to the ionosphere. Noise in the measurements at each frequency will be reduced by averaging data over approximately 50-ms intervals to yield smoothed observations of height along the subsatellite track. Successive 50-ms observations will be further averaged on the ground to give one observation of height every 3 s. The signal received by the altimeter will also be processed to determine wave height and wind speed. In particular, the averaged power as a function of time of the reflected pulse, which is the received waveform, will be processed to calculate significant wave height, and the signal strength will be used to calculate wind speed. The measure-

Table 4. Heritage of Topex altimeter

Satellite, yr	Frequency, GHz	Range Precision, cm (Averaging Time, s)	Wave Height Accuracy (Range)
Skylab, 1973	13.9	100 (0.3)	1–2 m
Geos-3, 1975	13.9	50 (0.2)	±25% (4–10 m)
Seasat, 1978	13.5	10 (1.0)	0.5 m or ±10% (1–20 m)
Geosat, 1985	13.5	5 (1.0)	0.5 m or ±10% (1–20 m)

Table 5. Topex/Poseidon altimeters

Parameter	Altimeters		
	Topex		Poseidon
Frequency, GHz	5.3	13.6	13.65
Radiated Power, W	20	20	2
Pulse Repetition Frequency	1,000	4,000	1,700
Pulse Compression Ratio	33,000	33,000	33,000
Instrument Precision, cm (3-s average)	2		4

ment of wind speed is of secondary importance, not being directly related to the primary mission goals. Hence, wind speed will be calculated using the best available algorithms, but little effort will be made to verify the accuracy of the measurement. Finally, height measured by each frequency, rate of change of height, significant wave height, receiver automatic gain control and waveform samples will be stored, then telemetered to the ground.

2. CNES Solid-State Altimeter

The CNES solid-state altimeter will be flown to gain experience with a new class of low-power, lightweight altimeters that could be operated on satellites of opportunity, thus providing for the long-term observation of the sea level, a goal of the World Ocean Circulation Experiment (see Section V.A). The signal received by the altimeter will be processed to give the same geophysical information as the NASA altimeter, but the two altimeters differ in design. The CNES altimeter will use separate circuits to lock on to the pulse received from the sea surface and to track the leading edge of the received pulse. The correction for ionospheric delay will be provided by the dual-frequency observations made by the Doris tracking system, used with models of the total electron content in the ionosphere. The correction for tropospheric water vapor will be made using data from the microwave radiometer. The altimeter is designed to measure the height of the satellite above the sea with a precision of ±4 cm by using a solid-state single-frequency altimeter operating at the K_u band (13.65 GHz) (Table 5). Current plans are to evaluate the accuracy of the altimeter measurements and then to incorporate the altimeter data into the geophysical data records.

3. Topex Microwave Radiometer

The Topex microwave radiometer will measure water vapor at the nadir (Table 6) to correct, with an accuracy of ±1.2 cm, the error in the altimeter measurements of height caused by pulse delay due to the water vapor. The radiometer will use refurbished electronics from the Nimbus-7 scanning multichannel microwave radiometer (SMMR) but differs somewhat from this instrument in its operation. Rather than scan, it will continuously observe the brightness temperature at nadir at three radio frequencies (18.0, 21.0 and 37.0 GHz) averaged over a period of 1 s. The longer observation time will yield more sensitive observations of brightness temperature than those from Nimbus-7, thus increasing the accuracy of the water vapor observations. The observed brightness temperatures will be periodically compared to an internal reference temperature and to cold space, and the difference temperature will be demodulated by a synchronous detector to correct for drift in the radiometer observations. After filtering, the brightness temperatures will be digitized and passed to the spacecraft data handling system.

Table 6. Topex/Poseidon microwave radiometer

Frequency, GHz	Field of View, km (Half Power Beamwidth, deg)	NEΔT, K*
18.0	42 (1.81)	0.11
21.0	35 (1.49)	0.11
37.0	22 (0.92)	0.15

*Noise equivalent error in temperature, averaged over 1 s

After transmission to the ground, the data will be further processed to determine the vertical columnar water vapor content necessary to correct the altimeter measurement of height for the influence of the wet troposphere.

4. Laser Retroreflector Array

The laser retroreflector will reflect signals from ground-based lasers allowing laser tracking stations to determine the range to the satellite with an accuracy of ±2-5 cm. These observations will be used to calibrate the altimeter measurement of height and to provide supplemental tracking of the satellite useful for calculating an accurate ephemeris. The altimeter will be calibrated by tracking the height of the satellite as it passes directly above laser calibration stations, planned to be located at Bermuda and Dakar, at the same time the altimeter measures the height of the satellite above the sea in the vicinity of the tracking station. The extrapolation of the difference between the laser and the altimeter measurements, when corrected for the height of the laser above sea level, yields an independent assessment of the accuracy of the altimeter measurement. In addition, if a worldwide system of laser tracking stations continues to be operating at the time of the Topex/Poseidon mission, data from these stations could be used to calculate an accurate ephemeris in the event of a failure of the primary tracking systems. The laser retroreflector assembly consists of corner cubes mounted in a conical ring around the perimeter of the altimeter antenna in a configuration similar to that on Seasat. The number of cubes will be sufficient to allow the array to be tracked with an adequate signal-to-noise ratio by existing laser tracking stations whenever the satellite is more than 20 deg above the horizon.

5. Tranet Beacon

The primary tracking system consists of an improved Tranet beacon that will be tracked by Tranet receiving stations widely spaced over the surface of the Earth and operated by the U.S. Defense Mapping Agency (Fig. 4). The beacon will transmit at frequencies of 400 and 150 MHz so that the influence of ionospheric delay can be reduced and will use an ultra-stable quartz oscillator with a stability of $\pm 5 \times 10^{-13}$ measured over a period of 1000 s to allow very accurate measurements of the Doppler shift produced by the satellite's velocity. The measurement of Doppler shift, made by radio receivers on the ground, yields observations of the time of closest approach and the distance from the tracking station to the satellite at this time. These data will then be used by orbit determination programs to calculate the satellite's ephemeris with a single-pass accuracy of ±13 cm (Table 7). By combining measurements of sea level made during all passes in a 10-20 day period, sea level can be computed with even better accu-

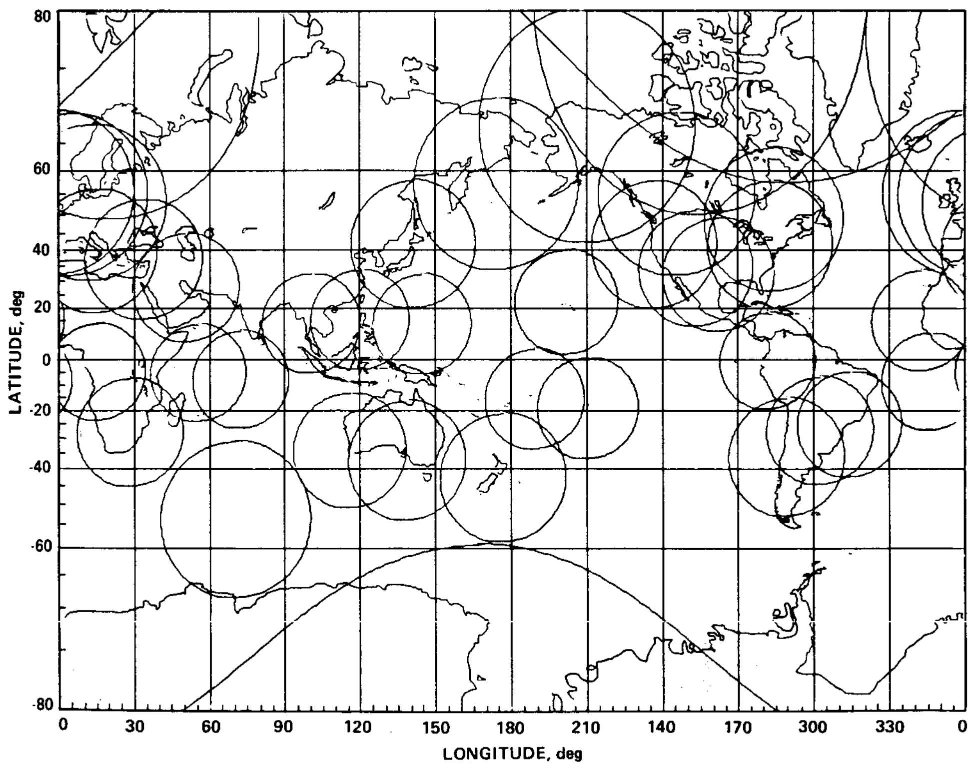

Fig. 4. The proposed coverage by Tranet receivers assuming a satellite altitude of 1334 km and a usable tracking elevation of 20 deg for the ground stations

Table 7. Topex/Poseidon tracking systems

System	Frequency, MHz	Ground Stations	Empheris Accuracy, cm
Tranet II	150 400	40	13
Doris*	401 2036	40–50	10
GPS*	1227 1575	3–8	10–15
Laser	Light	28	15–20†

*Experimental systems not yet tested or flown in space.
†Assuming a global network of tracking stations is operating during the mission.

racy (see Section IV.A.4.b). The beacon will be similar to that on Seasat but more stable in frequency.

6. Doris Receiver

The Doris system uses a two-channel receiver on the satellite to observe the Doppler signals from a network of 40 to 50 dual-frequency radio beacons distributed around the Earth (Fig. 5). The signal will be used for several purposes. First, the Doppler signal as a function of time will be used by orbit-determination programs to calculate the satellite ephemeris. Second, the difference in the signals at the two frequencies will provide an accurate correction for the influence of the ionosphere on both the Doppler signal and the signal used by the CNES altimeter. Finally, the Doppler signal will be used with orbit-determination programs to improve our knowledge of Earth's gravity field along the satellite's trajectory, leading to improved accuracy in the calculation of the satellite's ephemeris. The system is similar to Tranet, but will operate at higher radio frequencies so that the influence of the ionosphere will be less important, and it will use ultra-stable quartz

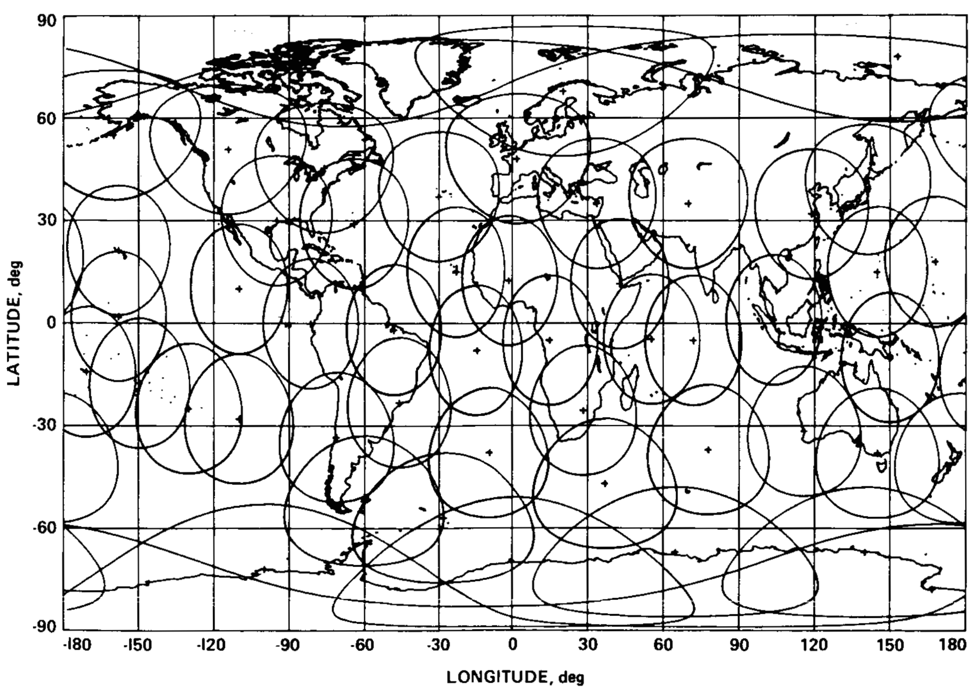

Fig. 5. The proposed coverage by Doris beacons, assuming a satellite altitude of 1334 km and a usable tracking elevation of 20 deg for the beacons

oscillators with a stability of 5×10^{-13} over a period of 1000 s and 10^{-11} per day.

The ground stations will be fully automated, allowing deployment in remote areas, especially in oceanic areas. Moreover, it is anticipated that a substantial number of these stations will be collocated with laser and Very Long Baseline Interferometry (VLBI) stations (to be linked to a precise and conventional reference system) and with tide gages and/or sea level measurements. The deployment of the network will be made by the Institut Geographique National of France. The first tests of the system are scheduled to begin around 1988 when Doris equipment will be carried by the Spot-2 satellite, the launch of which will depend, however, on the lifetime of Spot-1.

7. Global-Positioning-System Demonstration Receiver

A global-positioning-system receiver and processor will be carried as an experiment to provide a new type of tracking data for precision orbit determination: the difference in range between the satellite and receivers on the ground. The system will receive simultaneously the signals from four Global Positioning System (GPS) Navstar satellites using receivers on the spacecraft and at three or more positions on the ground. Present plans call for NASA to operate three stations and for the Defense Mapping Agency to operate three or more pending the outcome of negotiations with NASA. Other stations may be operated by other groups interested in precision orbit determination. Initial calculations by the Topex/Poseidon Orbit Determination Task Group (see Section III.A) indicate that by observing the difference between the signals from each GPS satellite as received at the satellite and at the ground, it may be possible to determine the satellite's position with an accuracy of ±6 cm without the need for accurate clocks on the satellites or on the ground. If the receivers on the ground are well spaced on the surface of the Earth, the system will be able to track the Topex/Poseidon satellite nearly continuously. The experiment will investigate the usefulness of this scheme for orbit determination and the accuracy of the resulting ephemeris.

C. Orbit

The orbit chosen for the Topex/Poseidon mission is a compromise among a number of conflicting requirements. The orbit must provide broad coverage of the oceans as frequently as possible without aliasing the tides to unacceptable frequencies, and it must be high enough to minimize atmospheric drag. Because the orbit is a compromise, it is worth considering the arguments influencing the selection.

First, the subsatellite track of the orbit must recur exactly at fixed intervals of time. If the subsatellite track repeats within ±1 km, then the influence of spatial variability of the geoid will be small (Fu, 1983b), less than ±1 cm on average. Thus an exactly recurring subsatellite track will enable the altimeter to measure the variability of surface geostrophic currents even when the geoid is unknown. But many orbits are available for which the subsatellite tracks recur exactly, and this requirement does not strongly constrain the orbit; sampling strategy does.

The sampling strategy for observations of the surface by the altimeter is determined by four important and interrelated properties of an orbit: the latitudinal extent of the grid traced out by the subsatellite point, the density of the grid, the time interval between repetitions of this grid, and the angle between the tracks at their intersections.

In order to sample as much of the ocean's surface as possible, the orbit should have an inclination as close as possible to 90 deg. This polar orbit, however, has ground tracks that are nearly parallel (Fig. 6), and this conflicts with a requirement that the subsatellite tracks cross at large angles so that the altimeter can measure both components of the surface geostrophic current with comparable accuracy.

A reasonable compromise between good crossing angles and good coverage is an orbit with an inclination near either 65 deg or 105 deg. These orbits have ground tracks that intersect at angles near 40 deg at the equator and that cover most of the open water in both hemispheres. (These orbits exclude

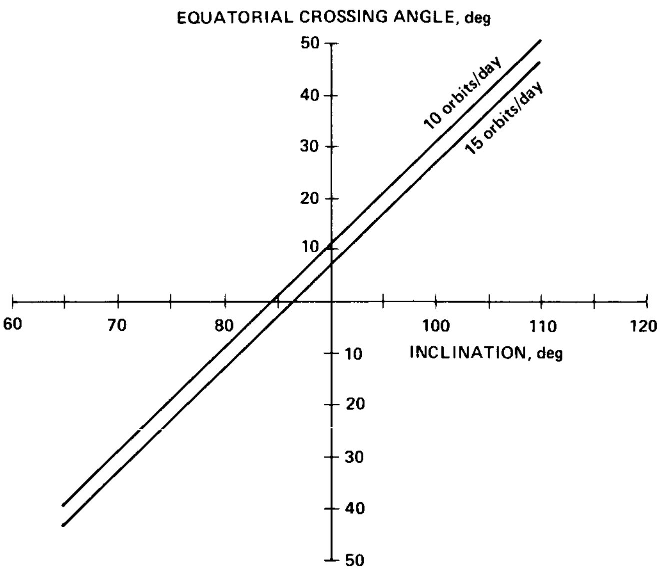

Fig. 6. The angle between intersections of subsatellite tracks as a function of orbital inclination with the number of orbits per day as a parameter

the Norwegian Sea and parts of the southern ocean, but these compromises seem both necessary and reasonable.)

The selection of orbital inclination is also strongly influenced by a desire to avoid orbits that are nearly synchronous with the sun so that the ocean surface is not sampled in phase with any of the major tidal constituents. To sample synchronously would alias the tidal constituents into long periods typical of the oceanic circulation and would make difficult the separation of the tides from the circulation. The rate at which the orbital plane of a circular orbit precesses is a function of inclination and geocentric radius (Fig. 7). Retrograde orbits (those with inclinations greater than 90 deg) with altitudes above 800 km are all nearly synchronous with one or another dominant tidal constituent (Figs. 7 and 8) and should be avoided. For this reason, it is preferable to choose a prograde orbit with an inclination less than 65 deg. Orbits at altitudes less than 1500 km at this inclination precess at a rate greater than 2 deg per day relative to the sun and are not close to being synchronous with any tidal constituent.

To minimize problems caused by atmospheric drag, the altitude of the satellite should be above 1300 km. Thus a nominal orbit should have an inclination near 65 deg and an altitude between 1300 and 1500 km. Within these bounds, it is then possible to find an orbit that recurs in exactly J days (Cutting, et al., 1978). All that is required is that the nodal

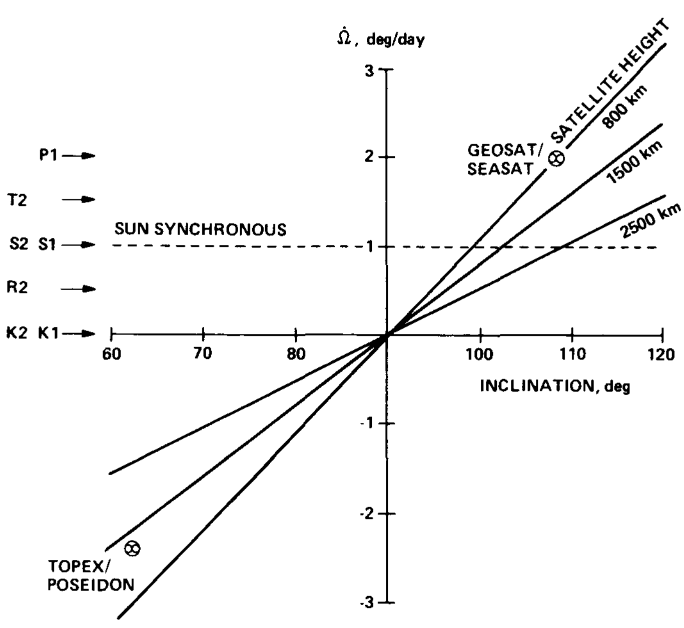

Fig. 7. The precession rate of the orbital plane as a function of inclination, with the altitude of the satellite as a parameter. To avoid aliasing the diurnal (*K*1, *S*1 and *P*1) and semidiurnal (*T*2, *S*2, *R*2, and *K*2) tides into long periods, orbits which are nearly sun-synchronous should be avoided. The indicated precession rates are those which alias the designated tidal constituent to zero frequency.

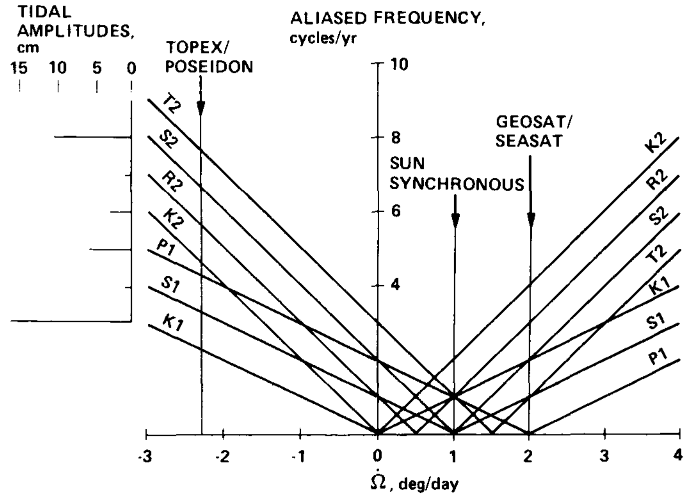

Fig. 8. The frequency into which the major tidal constituents are aliased as a function of the precession rate of the orbital plane, together with rough estimates of the tidal amplitudes (typical of the North Pacific). Note that, for sun-synchronous orbits, *S*1 and *S*2 are aliased to zero frequency, and that *T*2, *P*1, *K*1, and *R*2 are all aliased into the same frequency of one cycle per year. The Topex/Poseidon orbit is designed to avoid such undesirable aliases.

period be a suitable rational number; and provided that the repeat time is longer than a few days, many orbits are available.

The density of the grid traced out by the subsatellite track is set by the recurrence interval. The longer the interval, the tighter the grid. Assuming that the satellite's mean motion N in revolutions per day is $N = K + (I/J)$, where K, I, and J are integers, the period between repetitions of the orbit is J days; and the number of revolutions between repetitions is $KJ + I$. The spacing between ascending (or descending) subsatellite tracks at the equator is $40{,}075/(KJ + I)$ km. This distance decreases approximately as the cosine of the latitude (scaled by the inclination).

A reasonable compromise between grid density and frequency of observation (set by the recurrence interval) is an orbit with mean motion of 127/10 revolutions per day, which has a 10-day repeat period (also see Section IV.A.4). This interval provides a Nyquist frequency of 1 cycle per 20 days, which ought to be adequate for more than 90% of the global ocean, and a subsatellite track separation of 316 km at the equator (Figs. 2 and 3). But as a practical matter, the period of repetition is easily changed after launch, as long as the satellite is required to overfly no more than one verification site. The satellite will carry sufficient propellant to allow the repetition interval to be changed after launch, at least once, to any value between 3 and 20 days.

For planning the mission, the satellite is assumed to operate in an orbit with an inclination of 63.13 deg at an altitude of

1333.8 km (Farless, 1985). This orbit repeats the subsatellite track every 10 days, and it minimizes tidal aliases and air drag. The orbit has crossing angles between ascending and descending orbits of about 45 deg at 30-deg latitude; and it allows the satellite to observe most of the ocean except for small regions at high latitudes near Antarctica and in the Norwegian Sea. This should not be a problem because Topex/Poseidon is planned to fly at the same time as the European Space Agency's ERS-1 satellite, which will carry an altimeter in near-polar orbits. Data from this instrument can be used to extrapolate Topex/Poseidon data to higher latitudes. The more accurate Topex/Poseidon altimeter can be used to calibrate the ERS-1 altimeter, thus permitting coverage to be extended into the polar regions (see Section V.D).

D. Data Management and Verification

Three types of data will be useful for the Topex/Poseidon science investigations: (1) satellite data in the form of Intermediate Geophysical Data Records and Geophysical Data Records; (2) field data collected in support of the calibration and verification of the satellite data; and (3) historical data already archived at various locations plus contemporary oceanographic data collected by large-scale oceanographic experiments being planned to coincide with the Topex/Poseidon mission.

1. Satellite Data

Data from the NASA instruments will be processed by the Information Processing System (Fig. 9), which consists of two major facilities: the Topex Data and Information Facility (TDIF) operated by the Topex project and the NASA Ocean Data System (NODS) operated by the Jet Propulsion Laboratory. Data from CNES instruments will be processed by a satellite data processing facility operated by CNES, and will be distributed by the French data system AVISO. After processing their data to the level of Geophysical Data Records, each country will exchange data and make available to the scientific community the complete Topex/Poseidon data set (Fig. 10).

The Topex Data and Information Facility will accept the composite telemetry data from the spacecraft, the satellite ephemeris produced by the Goddard Space Flight Center, and supplementary information and will produce geophysical values such as the height of satellite above the sea, significant wave height, and atmospheric water vapor content. The facility will also maintain a record of the data distributed and will archive telemetry data, sensor data records, and geophysical data records.

In addition to processing data, the Information Processing System will also supervise the work necessary to verify the geophysical algorithms and the precise satellite ephemeris; it will collect the in situ data needed to support the verification and calibration of the Topex/Poseidon data; and it will distribute the satellite data to the National Oceanic and Atmospheric Administration's National Environmental Satellite, Data, and Information Service (NOAA NESDIS).

NODS is an archive for satellite observations of the oceans. Located at the Jet Propulsion Laboratory, it is designed to meet the needs of the oceanographic community for speedy, selective, and tailored access to satellite observations of the ocean. The system will provide regional and special formatting of Topex/Poseidon data, such as converting data from the grid defined by the subsatellite track to a grid defined by latitude and longitude; it will be a source for other satellite data, such as winds from the NASA scatterometer on NROSS that may be needed by the NASA Principal Investigators; and it will be an archive for all these data sets.

The French AVISO data system is similar to NODS, being a facility to process, distribute, and archive satellite oceanographic data. AVISO is organized under the Groupe de Recherches et d'Etudes en Oceanographie Spatiale (GREOS), a consortium of eight French governmental research organizations. AVISO is an approved project and will start in 1986. The facility will provide special processing of Topex/Poseidon data and will be a source of other appropriate satellite and ship data.

In support of the Topex/Poseidon mission, NODS will (1) distribute Geophysical Data Records and Interim Geophysical Data Records to NASA Principal Investigators, to the Topex/Poseidon verification team, and to the AVISO data system for distribution to the CNES Principal Investigators; (2) archive the Geophysical Data Records and Interim Geophysical Data Records; (3) contribute to the verification of Topex measurements by making available data necessary to verify the satellite measurements and computer programs to compare the Topex/Poseidon data with in situ or other data necessary for the verification work; and (4) provide computer time to develop programs needed by the Topex Project.

Five levels of data will be produced by the project:

(1) Telemetry data from the satellite transmitted to the Mission Operations System via the Tracking and Data Relay Satellite System. This is essentially raw data.

(2) Sensor Data Records consisting of a time-ordered, pre-edited record of partially processed data from the instruments in engineering units.

(3) Interim Geophysical Data Records consisting of all instrument data processed to final form in geophysical units, such as height of the satellite and water vapor

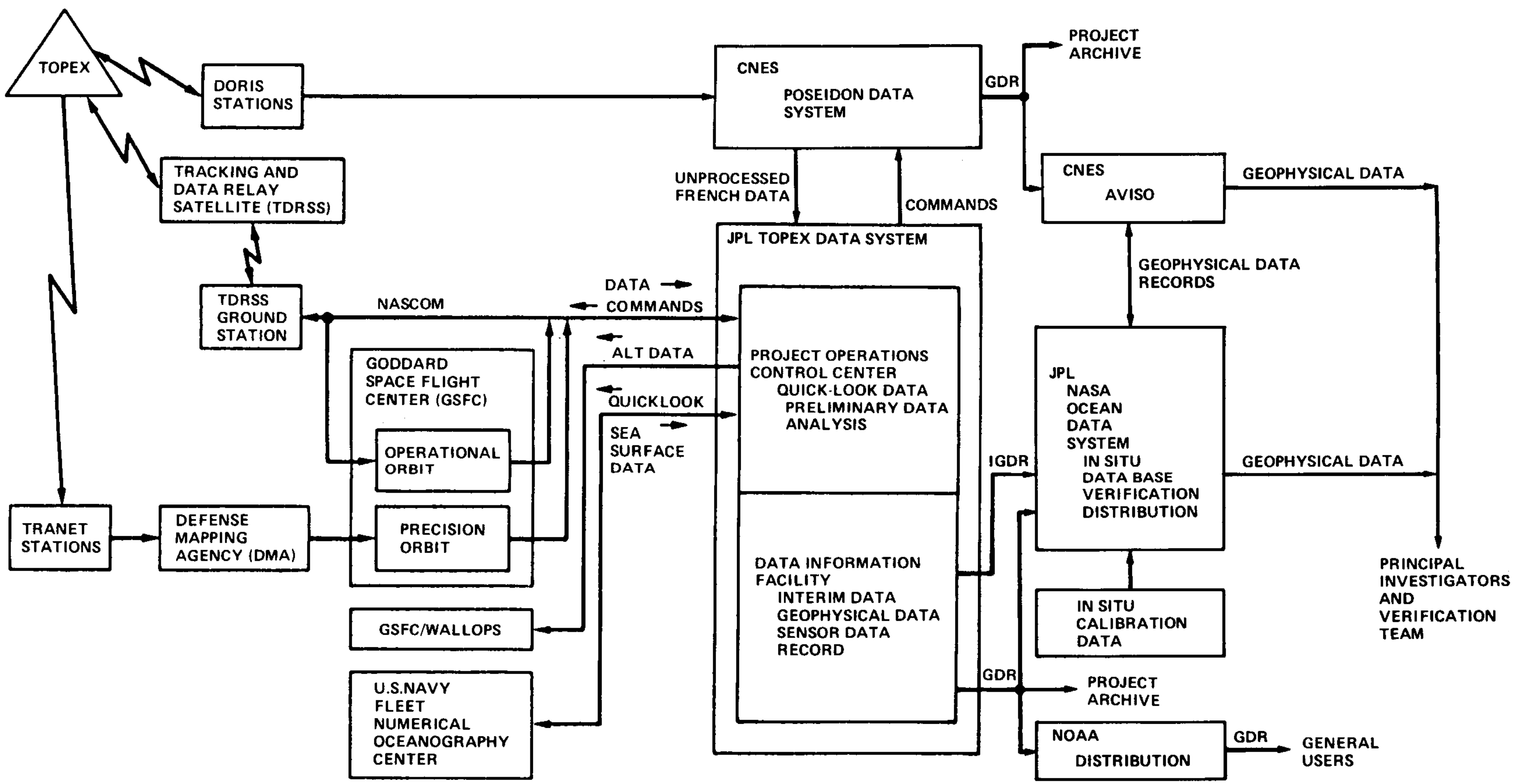

Fig. 9. The functional design of the information processing system

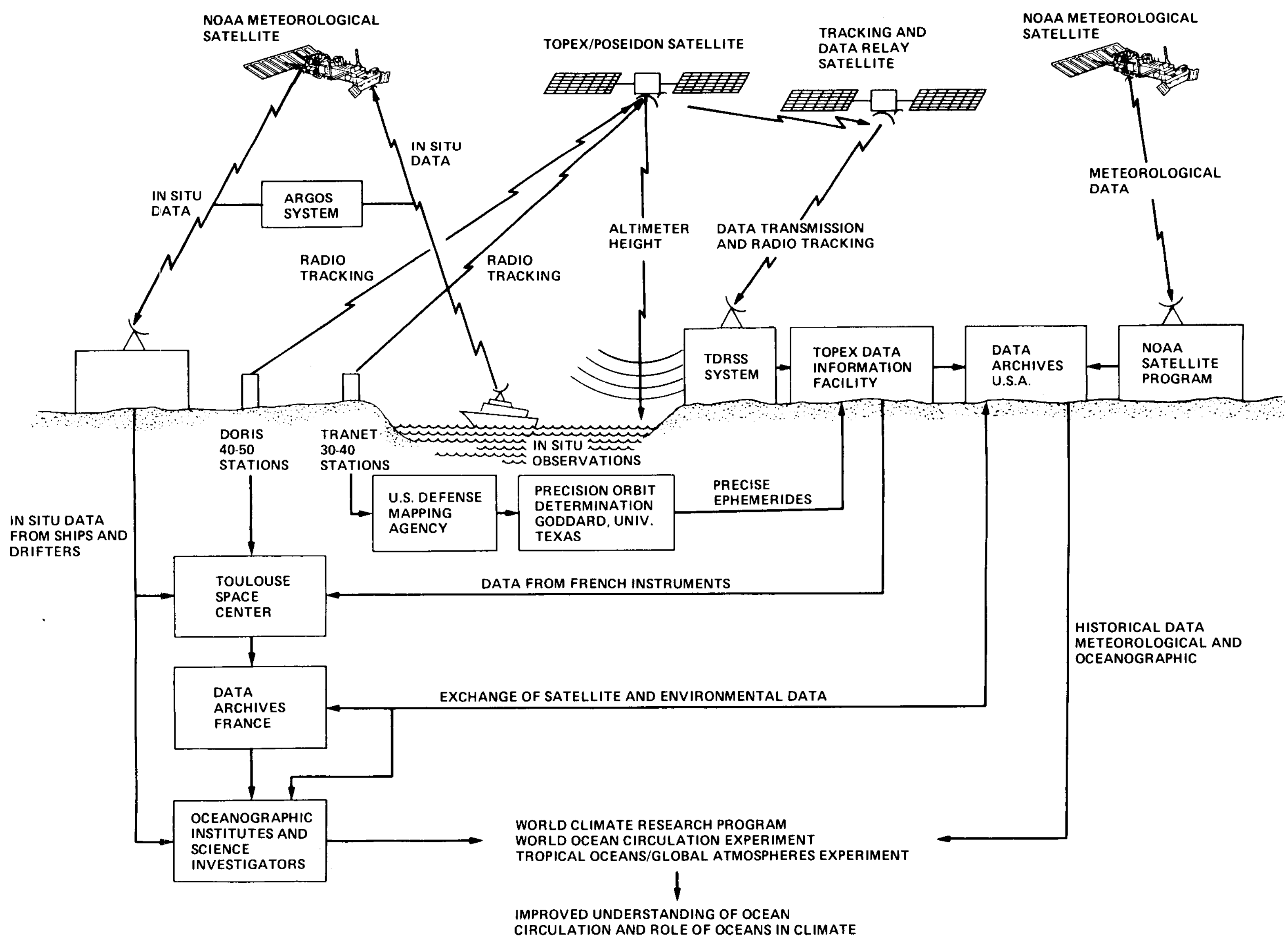

Fig. 10. Elements of the Topex/Poseidon program

density, except those which depend on the precision ephemeris. The Interim Geophysical Data Records will be available within 5 days after the receipt of telemetry and other data at the Information Processing System, and the records will be useful for planning the collection of oceanographic data that must be coordinated with the satellite observations. In general, the interim records will only be available during the verification period during the first six months after launch of the satellite. After this period they will be replaced by the Geophysical Data Records, although a small amount of interim data will be available to plan oceanographic experiments throughout the mission.

(4) Geophysical Data Records (GDRs) consisting of satellite data processed to final form including precise ephemerides calculated by the Precision Orbit Determination group (see Section II.A.9 for a listing of data that will be included in the GDR). The records will be available 6 months after receipt of initial satellite data. The delay is expected to shrink as the backlog of data acquired during the six-month verification period is processed and as the calculation of the accurate ephemeris is streamlined. The accuracy of the data record should improve as the project gains experience in processing the satellite data, *but the project does not plan to reprocess data*. New or revised processing algorithms may be implemented, but only after approval by the Principal Investigators. If the later data records prove to be significantly better than the earlier records, data could be reprocessed by external archives, such as the NASA Ocean Data System or the French AVISO, at the request of the scientific community.

(5) Quick-look data consisting of satellite measurements of wave height and wind speed. Those will be made available to the Fleet Numerical Oceanographic Center within 4 hours of the receipt of data at the project.

All data in the form of telemetry, Sensor Data Records, and Geophysical Data Records will be archived by the projects for the duration of the projects. Copies of the Geophysical Data Records will be sent as they become available to the NASA Ocean Data System, to the National Environmental Satellite, Data, and Information Service of the National Oceanic and Atmospheric Administration, and to AVISO for archiving and distribution to Principal Investigators and the wider scientific community. Principal Investigators selected by the NASA and CNES Announcement of Opportunity will be required to help write a data management plan that will specify the types of data that should be kept by national archives after the completion of the Topex/Poseidon mission.

The Topex/Poseidon data will be distributed to NASA Principal Investigators through the NASA Ocean Data System. The system will also archive and distribute other satellite data useful for the science investigators. The facility now has Geos-3, Seasat, and some Nimbus-7 and NOAA's AVHRR data, and in the future it will have wind data from the NASA scatterometer that will be flown on NROSS, and measurements of winds, sea ice, and water vapor measured by a multichannel microwave radiometer (SSM/I) operated by the Defense Meteorological Satellite Program.

Topex/Poseidon data required by CNES Principal Investigators will be distributed by the French AVISO data system. Pending agreement with the European Space Agency, AVISO may also be a source of ERS-1 data useful for Topex/Poseidon scientific studies.

2. Historical Data

Historical data useful for the Ocean Topography Experiment includes (1) data from Seasat and Geos-3 altimeters, (2) historical compilations of data from expendable bathythermographs that give the mean and seasonal variation of the thermal structure of the upper ocean, (3) measurements of density and trace elements of the deep water in the oceans, (4) measurements of the vertical structure of horizontal velocity in the ocean, (5) regional and global geoids, and (6) sea level measurements from tide gages. These data sets will be available through national archives and must be assembled as needed by the Principal Investigators working individually, or through large programs such as the World Ocean Circulation Experiment discussed in Section V. The Seasat, Geos-3, and geoid data are already available through the NASA Ocean Data System, and similar sets of data will be available through AVISO.

3. Verification of Measurements

The quality of the Topex/Poseidon data depends on the quality of the data from the satellite instruments and on the accuracy of the subsequent processing of the data. The testing necessary to ensure the accuracy of the processed satellite data will begin before launch and will continue throughout the life of the mission. Each step in the processing from raw data to geophysical information will be tested to ensure the accuracy and quality of the final data.

Pre-launch work will verify that algorithm specifications have been completed and are available one and one-half years prior to launch, that algorithms have been completed one year before launch, that the geophysical algorithms are correct and have been accurately encoded, and that ground-based data collection instruments and communication lines are operating properly. Before launch, algorithm verification tests will be conducted to confirm that all algorithms, both sensor and geophysical, have inherent precision and accuracy compatible with pre-launch specifications. Finally, the pre-launch readiness will be verified by an end-to-end test of the ground data system including measurement and processing functions. This will also include testing all interfaces with the Goddard Space Flight Center (GSFC) and Tracking and Data Relay System Satellite (TDRSS) facilities.

After launch, the first 30 days after the sensors are turned on will be used to determine that the spacecraft, sensors, communications links, and ground equipment are functioning according to engineering specifications.

After the 30-day engineering assessment, the collection of data for geophysical evaluation will begin. The verification of the geophysical measurements of satellite height, wave height, water vapor, and other variables will be done primarily for the next five months, although the work will continue for the duration of the mission but at a lower level.

Geophysical variables will be verified to the extent possible by comparison with in situ data. At the present time, instrumentation at Bermuda and Dakar (pending approval by Senegal) is expected to be the primary source of these data. Thus the Topex/Poseidon spacecraft will be placed in an orbit that passes directly over a laser on Bermuda and one near Dakar every 10 days, so that the orbital height measured by the laser can be directly compared with the height measured by the altimeters on the spacecraft. The elevation of each laser will be accurately surveyed to the height of tide gages in the oceanic area profiled by the altimeter. In addition, winds, waves, and water vapor will be measured at the calibration sites to determine the accuracy of the other measurements made by Topex/Poseidon instruments. The altimeter observations of the total electron content of the ionosphere will be compared with the electron content measured by incoherent-scatter radars at Jicamara, Peru, and Arecibo, Puerto Rico.

Verification after the initial 6-month period will consist primarily of monitoring data within the Information Processing System. If the monitoring reveals unexplained deviations in the expected values of the data, then a reverification will be considered.

The Topex/Poseidon precision ephemeris computed from the Tranet data will be verified for the project by the Goddard Space Flight Center and by the University of Texas (Fig. 11), and the ephemeris computed from Doris data will be verified by the Division Mecanique Spatiale of the Toulouse Space Center. The work will begin before launch with an extensive comparison of the Goddard and Texas systems. After launch, the accuracy of the ephemerides will be verified through analysis of tracking data residuals, by analysis of the difference in heights measured by the altimeter when it passes over oceanic areas with little natural variability, by comparison with heights measured by the laser at calibration sites and perhaps elsewhere, and by comparison with tide gage signals at selected sites. Finally, the ephemerides produced by the Goddard system, the University of Texas, and the Toulouse Space Center will be compared as a further means of establishing their accuracy.

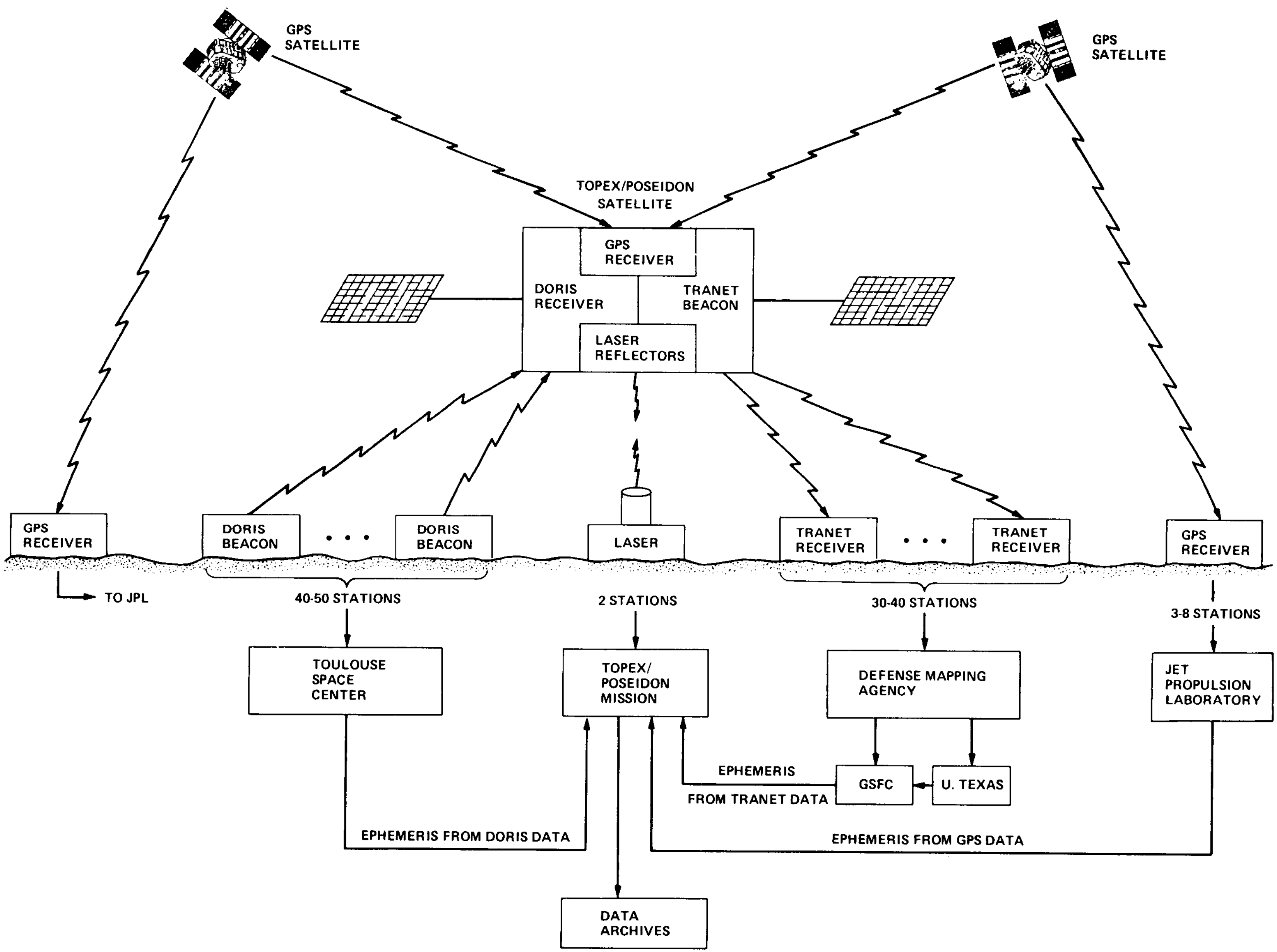

Fig. 11. Elements of the Topex/Poseidon precision orbit determination work

Section III
Measurement Accuracy

Altimetric measurements of sea level have many sources of error which are a complex function of position and scale. Thus it is important to examine in detail the extent to which altimeters can provide observations useful for oceanography.

First, the geocentric height of the spacecraft itself must be known; this requires both a tracking system or systems and mathematical models of spacecraft dynamics. These latter require the gravitational field of the Earth, which is imperfectly known but essentially constant in time, as well as adequate models of the forces due to the drag of the atmosphere and radiation from the sun and the Earth, all of which vary in time and space, depending upon the temperature (and hence density) of the upper atmosphere and the orientation of the satellite, among other variables.

Second, the calculation of oceanic topography from satellite measurements of sea level requires information about the shape of the equipotential surface, the geoid. This surface varies by roughly 100 m relative to a smooth reference surface, the reference ellipsoid. In contrast, the oceanic topography due to ocean dynamics varies only by roughly 1 m relative to the geoid. Thus, there is a great premium placed upon accurately determining the geoid if the permanent geostrophic velocities are to be found. On the other hand, if only time-dependent changes in the geostrophic velocity are required, an accurate geoid is not fundamentally necessary.

Third, the altimeter itself is subject to various errors: The precision of the Topex altimeter is approximately 2.0 cm, but a number of corrections must be applied to the apparent altimetric height to calculate true height with an accuracy comparable to the precision. These include corrections for the amount of water vapor in the atmosphere and the number of free electrons in the ionosphere, both of which change the speed of electromagnetic radiation and hence the apparent height measured by the altimeter. Furthermore, the sea surface is complex, rough, and moving; and this too influences the height measurement.

Finally, relating the surface geostrophic velocity to velocities at depth involves the density field of the ocean below the surface. This cannot be obtained from space but requires subsurface observation and modeling that will be provided by other oceanographic experiments.

A. Orbit Errors

Uncertainty in the ephemeris of the Topex/Poseidon satellite is the largest source of error in the altimeter measurement of sea level. The ephemeris is the tabulated values of the position of the satellite as a function of time calculated from observations made by satellite tracking systems. If the satellite altimeter is to map the permanent topography of the sea with an accuracy sufficient for studies of permanent geostrophic currents, the vertical component of the ephemeris must be known with an accuracy of better than ±13 cm (see Section IV.A.5). To provide this accuracy, the Topex/Poseidon mission includes a precision orbit determination program consisting of radio frequency and laser tracking systems, a software system to calculate an accurate ephemeris using the tracking data, and continuing research to understand and reduce errors in the calculation of the ephemeris. (Note that lasers will be used primarily for verifying the altimeter's measurement of height and the accuracy of the satellite's ephemeris. They would be used for tracking only if the primary tracking data were unavailable.)

In theory, the ephemeris can be calculated from Newton's equations of motion by knowing the forces acting on the satellite, together with occasional measurements of the initial and later positions of the satellite. In practice the forces are not known with sufficient accuracy to permit accurate calculations of the ephemeris between infrequent observations of the satellite's position. As a result, nearly continuous measurements of the satellite's velocity or position made by a tracking system are necessary to constrain the integration of the equations of motion. Thus, an accurate ephemeris requires accurate estimates of the forces acting on the satellite, numerical integrations of the equations of motion, and nearly continuous and accurate measurements of the satellite's velocity or position. The accuracy and frequency of the measurements of velocity or position depend on the measurement system. The primary tracking systems will be the Tranet and Doris Doppler tracking systems. These will be supplemented by observations from the experimental GPS receiver. All except the laser can provide nearly continuous observations of the position or velocity of the Topex/Poseidon spacecraft.

The accuracy of the radio frequency systems is influenced by variations in the velocity of the propagation of the radio signals caused by tropospheric water vapor and free electrons in the ionosphere. The latter are especially important for radio frequencies less than 1 GHz; hence, all the systems use two frequencies to reduce the effect. The distribution of stations is also important. Ideally, tracking stations should be uniformly distributed to keep the satellite in view at all times. Although a considerable effort has been made to deploy stations in remote areas, there are still some gaps in tracking coverage. Both pulse delay and station distribution have been accounted for, along with other sources of error, in the estimates of ephemeris accuracy included in Table 7.

Data from the Tranet stations will be collected by the U.S. Defense Mapping Agency and then forwarded to the Goddard Space Flight Center (GSFC) and to the University of Texas at Austin. At GSFC the data will be combined with laser data and incorporated into numerical programs to produce accurate satellite ephemerides that will be forwarded to the Topex project for inclusion in the Topex data stream. Data from the GPS receivers and from the Doris beacons will be analyzed and distributed by the Telecommunication Science and Engineering Division of the Jet Propulsion Laboratory and by the Toulouse Space Center, respectively. At the Toulouse Space Center, Doris data will be combined with laser data and incorporated into numerical programs to produce accurate satellite ephemerides that will be included in the Topex/Poseidon data stream. The ephemerides will also be compared with ephemerides produced by GSFC in order to help assess the accuracy of the Topex/Poseidon orbit calculations.

The accuracy of the integrations of the equations of motion depends critically on knowledge of the forces acting on the satellite. In relative order of importance, these are as follows:

(1) The spatially varying components of the Earth's gravity field. The long-wavelength components of the gravity field have been well measured by tracking low Earth-orbiting satellites, but the shorter wavelengths are less well known, coming in part from regional surveys of gravity at the Earth's surface and in part from tracking satellites in many different low orbits. To ensure that gravity at the height of the Topex/Poseidon orbit is known well enough that Tranet data can be used to compute orbits with an accuracy of better than 13 cm, the Topex project has funded further analysis of existing data from well-tracked satellites. The goal of this work is to reduce errors in the knowledge of gravity along the Topex/Poseidon trajectory to one half the present errors by the time of launch of the satellite. There are also parallel efforts in France to improve the knowledge of the gravity field using previously recorded data together with new data expected from the Doris system on Spot-2 through cooperative work by GRGS at Toulouse and the Deutsches Geodätisches Forschungsinstitut at Munich.

(2) Solar and terrestrial radiation. If gravity is sufficiently well known, the coefficient of radiation pressure can be recovered with sufficient accuracy from tracking data that the amplitudes of the radial error in the satellite ephemeris due to this effect will be acceptably small. The error is directly proportional to the satellite's area-to-mass ratio, so the satellite has been designed to be as heavy and compact as possible with accurately known surface areas.

(3) Atmospheric drag. The influence of this force has been minimized by selecting an orbit that is well above regions where the atmosphere is dense enough to cause a problem and will be minimized by flying a compact, dense satellite.

(4) The perturbing effect of oceanic tides. These effects will be recomputed using existing tracking data and will be known with sufficient accuracy.

(5) The gravitational attraction of the moon and sun. These too are known with sufficient accuracy.

(6) Outgassing from the satellite. The mass of the satellite varies because of outgassing (which itself can push the satellite) and because of mass expelled during maneuvers. The change in mass not only enters directly into the dynamical computations of the orbit but also changes the position of the satellite's center of mass, the point of reference for the orbit computations.

The expected accuracy of the Topex/Poseidon ephemeris based on Tranet data has been estimated by the Precision Orbit Determination Task Group. They assumed the satellite would be tracked by the present improved Tranet network of 40 stations using accurate frequency standards and that the satellite would orbit at a height of 1300 km at an inclination of 63 deg. The results of the study, summarized in Tables 2 and 7, indicate that uncertainties in the knowledge of gravity produce the largest errors, but that errors in tracking-station locations and the unmeasured influence of the ionosphere on the radio tracking are also important.

Similarly, the expected accuracy of the Topex/Poseidon ephemeris based on Doris data has been estimated by the French Doris Orbitography and Geopotential Evaluation (DOGE) Group. The ephemeris accuracy indicated in Table 7 is a result of the very dense coverage (50 stations with very few gaps) and the high accuracy of the Doris tracking data (0.3 mm/s).

The errors in the gravity field will introduce some geographical correlation into the radial ephemeris errors. A study is now underway to estimate the magnitude and correlation distances associated with anticipated errors in the gravity field. However, the amplitudes of the correlations are expected to be less than 5 cm, while the correlation distance will be many thousands of kilometers.

Finally, measurements made in a satellite coordinate system must be referred to a geodetic coordinate system. The two systems are related through measurements of the length of day and polar motion. By the time of the flight of the satellite, the two systems will be integrated with an accuracy sufficient for studies of ocean dyanmics. The work necessary to produce a unified, accurate geodetic coordinate system is already being undertaken by the international geodetic community, including two major field programs, the Monitor Earth Rotation and Intercompare Techniques (MERIT) and the program to establish and maintain a Conventional Terrestrial Reference System (COTES) sponsored by the International Union of Geodesy and Geophysics and the International Astronomical Union.

A good estimate of the potential accuracy of the Topex/Poseidon ephemeris can be gained from the Seasat experience (Fig. 12). Based on pre-launch knowledge of the gravity field and other forces, the error in the first calculations of the radial component of the Seasat orbit determined by lasers was about 5 m. After tailoring the gravity field using Seasat laser and NASA radio tracking data, the error was reduced to approximately 1.8 m. With the inclusion of some Geos-3 altimeter data into the gravity model, the error in the ephemeris was reduced to 1.5 m. This gravity field, PGS-S3, was used

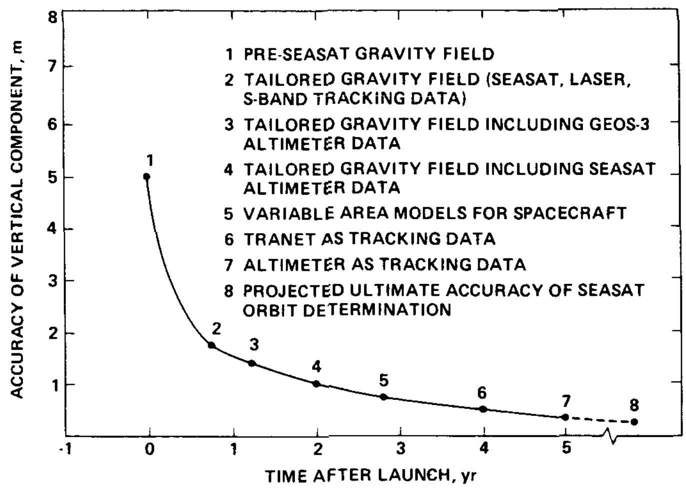

Fig. 12. Evolution of Seasat orbit determination accuracy

to produce the ephemeris used in the Seasat Geophysical Data Records.

Recent developments have led to new Seasat ephemerides with an accuracy of around 60 to 70 cm in the radial component, and further improvements are expected. The more accurate ephemerides are based on an improved gravity model and on the development of variable area models for the computation of more accurate drag and radiation forces acting on the Seasat spacecraft. In addition, the Defense Mapping Agency has released some Seasat Tranet tracking data to supplement the laser and NASA tracking data.

B. Altimeter Errors

An altimeter operates by sending out a short pulse of radiation and measuring the time required for the pulse to return from the sea surface. This measurement gives the height of the instrument above the sea surface, provided that the velocity of the propagation of the pulse is known. The accuracy of the measurement depends then (1) on a knowledge of the velocity of a radar pulse and (2) on the ability of the instrument to determine the precise arrival time of the reflection. The former depends on the media through which the pulse propagates, and it is discussed in the next section; here we consider the latter problem.

The length of the transmitted pulse is determined by the bandwidth of the transmitted signal. This is 320 MHz for the Topex 13.6-GHz altimeter, and the pulse length, in a simplified analysis, is roughly 3.125 ns or 0.9 m. To measure range with 2-cm accuracy, the instrument must accurately calculate the midpoint of the leading edge of the received pulse (Fig. 13). The inaccuracies in this calculation result from several processes.

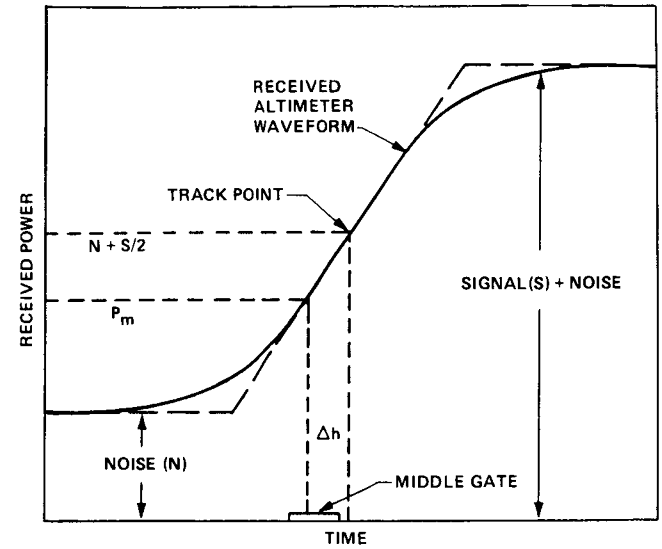

Fig. 13. Schematic of the received altimeter waveform where *N* is receiver noise, *S* is the received signal, Δh is the width of the tracker gates used to find the track point, and P_m is the power received by the gate

(1) The shape of the pulse is uncertain due to receiver noise and to random variability in the shape of pulses reflected from the sea surface. This produces instrument noise, which is reduced by averaging together many pulses to obtain a smooth mean pulse.

(2) The amplitude of the received pulse varies as the reflectivity of the surface varies. An automatic gain control (AGC) circuit attempts to compensate for this, but rapid changes in amplitude mislead the circuit that tracks the position of the leading edge of the pulse. This produces tracker error. The CNES altimeter will use separate tracking and acquisition circuits, thus reducing tracker error.

(3) Rapidly changing satellite height also produces tracker errors. These are reduced by using an orbit with small eccentricity.

(4) If the subsatellite point is near the edge of the area illuminated by the altimeter, the reflected pulse is distorted. This is a pointing error that is avoided by accurate control of the satellite's attitude or by a posteriori determination of attitude.

(5) Large steep ocean waves stretch the pulse and distort its shape. Thus the leading edge of the stretched pulse is more difficult to determine, leading to greater instrument noise; and the distorted shape of the pulse produced by wave skewness leads to tracker error. In addition, waves increase the size of the area on the sea surface illuminated by the radar, decreasing the time required to obtain independent pulses from the sea surface (Walsh, 1982). This increases altimeter noise if the time between pulses is not sufficiently short. The pulse repetition rate for the Topex altimeter is approximately 4.5 kHz (1.0 kHz for Seasat), while the optimum rate is 1.19 kHz for 2-m waves, rising to 4 kHz for 20-m waves. Thus the altimeter noise will be small for all but the largest waves at the expense of slight oversampling at lower wave heights. The pulse repetition rate for the CNES altimeter is 1.7 kHz.

Extrapolating the errors and noise observed in the Seasat and Geosat altimeter data to the Topex design leads to an expected error of 2 cm for 2-m significant ocean wave heights when the altimeter measurements of height are averaged for 3 s. Simulations of tracking errors by Hayne and Hancock (1982) and preliminary testing with a laboratory model of the proposed Topex radar altimeter lead to much the same result. Once tabular corrections are applied to the altimeter measurements, the on-board tracker is expected to perform with adequate accuracy, eliminating the need for more elaborate processing of altimeter data on the ground.

The altimeter is designed to track uniform time rates of change in altitude but has some difficulty with acceleration. For the Topex/Poseidon altimeter, an altitude error of 0.07 cm can be expected for a typical acceleration of 0.6 cm/s^2.

The bias in the altimeter measurement of height can be divided into a constant and a long-term drift with variation over many days. The constant bias will be determined to within centimeters by direct measurement using lasers at two calibration sites. This post-calibration bias error is fixed for all time, so it will have no influence on the Topex/Poseidon mission and therefore is not included in the error budget. On the other hand, the long-term drift must be accounted for. Drift can be measured with an on-board calibration system to within 2.0 cm, and independent techniques are being investigated to monitor drift with an accuracy of 1-2 cm over the lifetime of the mission. One such technique compares the mean height of the satellite orbit with the global mean value of the altimeter measurement of height. Initial studies using Seasat data indicate that the difference could be monitored with an accuracy of ±2 cm. If this accuracy were possible, the value of the difference as a function of time could also provide important new information about interannual changes in heat storage in the ocean.

The uncertainty in relating time measured by the altimeter's clock and time measured on the ground introduces a timing error proportional to $\dot{h}\Delta t$, where Δt is the timing error and $\dot{h}$ is the rate of change in height of the instrument. To limit this error, a specification of 100 μs has been placed on the altimeter timing accuracy, and the maximum value for the mean orbital eccentricity has been specified as 0.001 in order to bound $\dot{h}$ at 20 m/s. These specifications result in a negligible 0.2-cm altitude error due to timing errors.

C. Errors Due to the Environment

The atmosphere and ionosphere slow the velocity of radio pulses at a rate proportional to the total mass of the atmosphere, the mass of water vapor in the atmosphere, and the number of free electrons in the ionosphere. In addition, radio pulses do not reflect from the mean sea level but from a level that depends on wave height. While not large, the errors due to these processes cannot be ignored and must be removed (Stewart, 1985).

1. The Ionosphere

At the frequencies used by the Topex/Poseidon altimeters, the propagation velocity of a radio pulse is slowed by an amount proportional to the number of free electrons along the path, the ionospheric total electron content (TEC), and inversely proportional to the square of the radio frequency. The retardation of velocity causes the altimeter to slightly overestimate the range to the sea surface by typically 0.2-20 cm at 13.60 GHz. The amount varies from day to night (very few free electrons at night), from summer to winter (fewer during the summer), and as a function of the solar cycle (fewer during solar minimum).

The magnitude of the ionospheric range error will be measured by using an altimeter that operates at 5.3 GHz and 13.6 GHz. Combining the observations of range at the two frequencies gives both the electron content and the true range. After correction for ionospheric influences, the dual-frequency altimeter will have a total error of ±2.4 cm due to instrument and ionospheric influences.

The Poseidon altimeter uses a single frequency (13.65 GHz). To correct for the pulse delay in the ionosphere, the Poseidon project will use a model of the ionosphere electron content based on extensive measurements of the total electron content made by the Doris tracking stations. More than 250 measurements a day with a global coverage will either constrain physical parameters of existing models or allow the development of empirical new models. First results using observations of a Tranet satellite during a geodetic experiment (MEDOC) are encouraging. The Doris data from Spot-2 will validate the algorithms. The expected final accuracy in correcting for ionospheric errors is 2 cm.

2. The Troposphere

The propagation velocity of a radio pulse is also slowed by an amount proportional to the mass of the atmosphere and the quantity of water vapor along the path length. The former is nearly constant, but water vapor is quite variable and unpredictable.

The mass of the atmosphere varies by only about ±3% from a mean value, a variation corresponding to a height error of ±7 cm. If we assume that the surface pressure is known to ±3 mbar, the uncertainty in path length will be ±0.7 cm. Surface pressure with this accuracy will be obtained from the Navy Fleet Numerical Oceanography Center and will be incorporated into the altimeter Geophysical Data Record. Measurements of surface pressure are also collected on a global and daily basis by the European Center for Medium Range Weather Forecasting in Reading, U.K., and they too will be available.

Water vapor in the troposphere produces a height error of 6–30 cm. To correct for this error, water vapor within the altimeter beam will be measured directly by the Topex microwave radiometer using observations at either 18 and 21 GHz or 21 and 37 GHz. The analyses of the data from the Seasat Scanning Multichannel Microwave Radiometer (SMMR) indicate that pairs of brightness temperatures measured by this instrument give columnar water vapor with an accuracy of 4 kg/m^2, yielding a correction accurate to 2.3 cm (Tapley, et al., 1984). The more accurate Topex microwave radiometer is expected to measure water vapor with an accuracy of 2 kg/m^2 or better, which corresponds to an uncertainty of ±1.2 cm in path length.

3. Ocean Waves

Troughs of waves tend to reflect altimeter pulses better than do crests. Thus the centroid of the mean reflecting surface is shifted away from mean sea level towards the troughs of the waves. The shift, termed the electromagnetic bias, causes the altimeter to overestimate the height of the satellite above the sea surface.

The nature of the electromagnetic bias has been investigated using airborne radars and lasers capable of determining the strength of the vertically reflected signal as a function of the displacement of the reflecting area from mean sea level, for various sea states.

Observations using 10 GHz, 36 GHz, and laser radiation (Choy et al., 1984; Walsh, et al., 1984; Hoge, et al., 1984) indicate that the electromagnetic bias decreases with frequency, being –3.2 ±0.3% of significant wave height at 10 GHz, –1.0 ±0.3% at 36 GHz, and 1.4 ±0.8% at light wavelengths.

The scatter in the observations at 36 GHz is a function of wind speed and the skewness and kurtosis of the probability distribution of sea surface elevation due to the waves on the sea surface. Based on these observations and studies of Seasat and Geos-3 altimeter data, the electromagnetic bias will be determined with an accuracy of 1% significant wave height using only the measurements of wave height made by the altimeter. No attempt will be made to account for the influence of the skewness of the sea surface elevation because this influence is relatively small.

More work is required to improve further the accuracy of the correction. Studies are now being made in laboratories (water tanks) in order to better understand the dynamics and distribution on longer waves of the short capillary waves causing the electromagnetic bias and their influence on radar scatter at different radio frequencies, incidence angle, and sea state conditions (swell, foam, etc.). The extrapolation of these results will be made at sea using altimeters and laser profilometers carried on aircraft along with other instruments to profile the surface wave field and to measure other surface variables.

4. Rain

Rain attenuates the altimeter pulse, and heavy rain greatly reduces the echo from the sea surface. Light rain tends to produce rapid changes in the strength of the echo as the altimeter crosses rain cells. Both effects degrade the performance of the altimeter, and altimeters usually fail to operate accurately if the rain rate exceeds 5mm/hr. Data contaminated by rain will be tagged and ignored. Fortunately, rain is rare and ignoring data from rainy areas is acceptable.

D. Geoid Uncertainty

The geoid must be directly subtracted from the sea level measured by the altimeter to yield the oceanic topography caused by permanent surface geostrophic currents. The time-variable currents can be computed without an accurate geoid because the satellite orbits will repeat with a very high degree of accuracy.

Early calculations of the geoid were based on terrestrial gravity data. Later analyses used observations of the perturbations of satellite orbits to obtain the coefficients of a spherical harmonic expansion of the Earth's gravitational potential. These coefficients were then combined with terrestrial gravity data to obtain very high degree (180) spherical harmonic expansions (Rapp, 1981) or very detailed estimates of geoid undulation in local areas (Torge, et al., 1983).

Lambeck and Coleman (1983) described and compared many of the sets of geoid coefficients that have been determined in the past 24 years. Lerch, et al. (1985), also made a comparison of the most recent geoid models. Currently the most accurate set based only on the analysis of satellite data is the GEML2 field (Lerch, et al., 1982), which is complete to degree 20, that corresponds to a half-wavelength of 1000 km. Based on the estimated accuracy of the coefficients of this expansion, the global root mean square accuracy (commission error only) of the GEML2 solution to degree 20 is ±1.6 m, or ±18 cm if only coefficients to degree 6 are considered. The geoid undulation accuracy, by degree, for the GEML2 coefficients is shown in Fig. 14. The accuracy estimates, for the very low degrees, may be pessimistic (Wagner, 1983). The substantial improvement in geoid undulation determination at long wavelengths in the past few years has been due to the inclusion of laser ranges to the Lageos satellite in the solutions. This improved gravity field has been successfully used by Engelis (1983, 1984) to detect the large-scale ocean circulation using Seasat altimeter data. Tai and Wunsch (1983) used the GEM9 model to determine dynamic topography in the Pacific region, and Tai (1983) has described general procedures for the circulation analysis.

A set of coefficients (GRIM3-L1) complete to degree and order 36 in the spherical harmonic expansion of the gravitational field that combines satellite (including Lageos) and terrestrial gravity data has recently become available (Reigber, et al., 1985). The undulation differences between this solution and GEML2 are shown in Fig. 14. Up to degree and order 6, the cumulative difference is ±40 cm, while up to degree and order 20 it is ±2.36 m. In oceanic regions, the maximum difference between the two solutions is 1.3 m (to degree 6) and 5 m (to degree 20).

The errors that have been considered so far have been in the spectral domain. If we wish to calculate the height of the

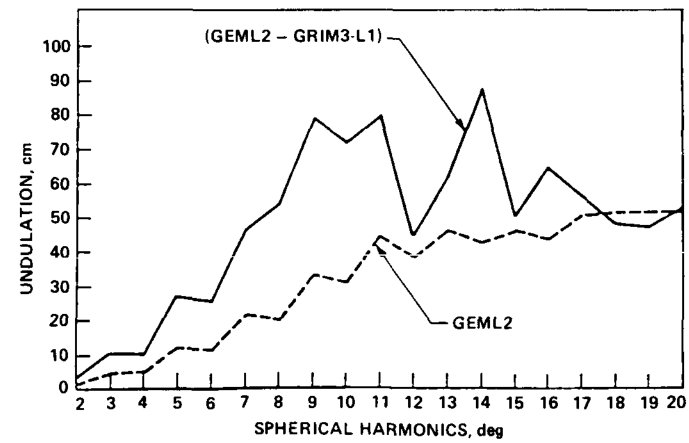

Fig. 14. Geoid undulation comparisons by degree

geoid at a point (i.e., one with all frequency components considered) or an average undulation in a geographic region, the effect of the nonestimated coefficients needs to be considered. Nonestimated coefficients are those of higher degree and order than those used to calculate a smoothed geoid. An approximate estimate for the effect of neglected terms above degree N is $64/N$ m so that the omission error is about ±3 m for the degree-20 solutions and 40 cm (perhaps an optimistic estimate) for recent high-degree (180) solutions that incorporate terrestrial gravity data (Rapp, 1981). The accuracy of a mean geoid undulation can be substantially better than a point value depending on the size of the area in which the mean is taken and the weighting operator or filter that is used to define the average.

To obtain short wavelength geoid undulations, it is necessary to incorporate terrestrial gravity data with information about longer wavelength coefficients of the gravitational potential. Such geoids have already proved valuable for determining the dynamic topography of the ocean (Ganeko, 1983; Cheney and Marsh, 1981b). Torge, et al. (1983), have combined the GEM9 coefficients of the gravitational potential with 1-deg × 1-deg and 6-min × 10-min mean gravity anomalies to compute a geoid for much of Europe, including surrounding oceans and seas. The accuracy of a point undulation in this calculation is estimated to be ±86 cm. This accuracy estimate should not be construed as typical for all oceanographic areas as sufficient gravity data do not exist for the accurate estimation of the gravity anomaly averaged over small areas that are needed for these computations.

Substantially improved geoid determinations will result from the gravity-field improvement studies now being undertaken by the GSFC and the University of Texas. In the future, further substantial improvements in knowledge of the geoid can be expected from the proposed Geopotential Research Mission (GRM) designed to measure Earth's gravity field from space (Taylor, et al., 1983). A nominal mission would include two satellites approximately 300 km apart in a polar orbit 160 km above the earth. Using satellite-to-satellite tracking (SST) techniques, significant improvement in gravity anomalies and geoid undulations can be expected (Jekeli and Rapp, 1980; Douglas, et al., 1980; and Breakwell, 1979). Assuming that the distance between the two satellites could be tracked with an accuracy of ±1 μm/s, Jekeli and Rapp have estimated the following accuracies for geoid computations over specified blocks or areas: ±16 cm for 30-min × 30-min areas; ±3.7 cm for 1-deg × 1-deg areas; and ±1.5 cm for 2-deg × 2-deg areas.

These estimates of accuracy from GRM may also be considered as a function of wavelength or spherical harmonic degree. For example, at degree 100, which has a half wavelength of 200 km, the undulation accuracy is ±0.10 cm. If the error from all the coefficients up to degree 200 is considered, the accuracy of the band-limited geoid undulation would be ±0.46 cm, as shown in Fig. 15.

To obtain geoid undulations with still shorter wavelengths, it will be necessary to supplement the GRM data with detailed ship gravity measurements and/or accurate bathymetric data. The latter data can be used to estimate the perturbations in the gravitational potential at the ocean surface caused by the bathymetry.

Another project to improve knowledge of the gravity field called Gradio has begun under the auspices of CNES and ONERA (Office National d'Etudes et Recherches en Aerospatiales). The project will measure the gravity gradient using gradiometers on a satellite. The gradiometers will measure the differential accelerations using an array of ultra-precise capacitive sensors. The project has been submitted to the European Space Agency (ESA) for a possible flight in 1995 on a dedi-

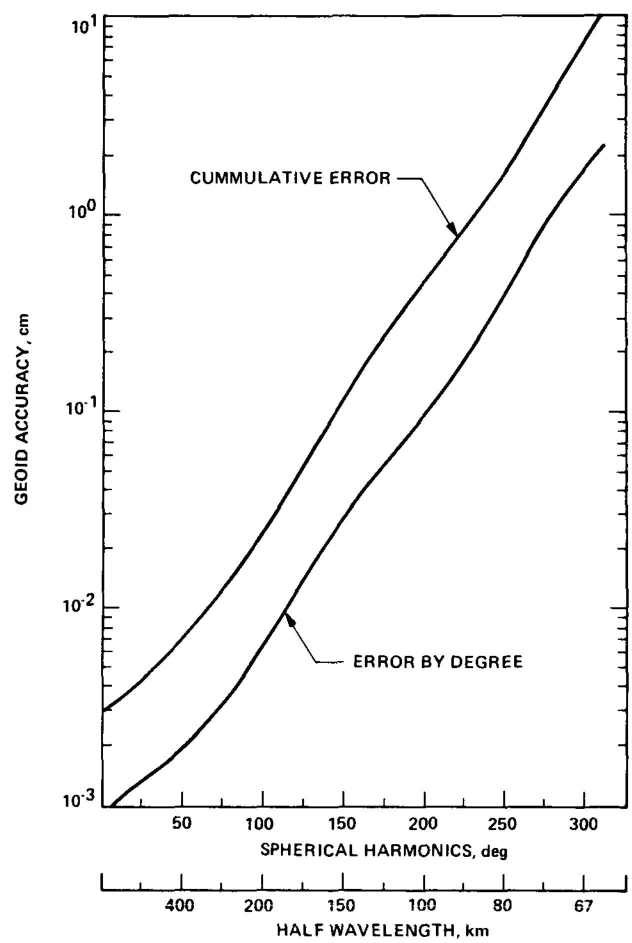

Fig. 15. Geoid undulation accuracy, by wavelength, for a geopotential research mission having a tracking error of ±1 μm/s, flying at a height of 160 km, and operating for 6 months

cated platform at an altitude of 200 km. The accuracy of the gravity observations is expected to be similar to that of GRM.

The above discussion indicates that current gravity models are just now becoming sufficiently accurate so that long-wavelength patterns of ocean circulation can be detected. In the next few years, the errors in our knowledge of Earth's gravity will be reduced to one-half the current error by reprocessing previously collected satellite tracking data, being done as part of the Topex/Poseidon gravity field improvement program. To reduce the error by one-tenth to one-hundredth of the present value, a level needed for various studies, the data from GRM or Gradio missions are required. Detailed gravity information today provides undulation accuracies at the ±90-cm level, much of this error being long wavelength in nature so that undulation differences over short distances (100 km) can be computed to an accuracy of ±10 cm if sufficient gravity data are available (Engelis, et al., 1984).

E. Tides

Not only do the tides introduce errors into the determination of geostrophic velocity, but they are of considerable interest in their own right. Existing numerical tide models (Schwiderski, 1980) suggest that, at best, a priori corrections good to 10 cm can be made to the altimeter measurements of the global ocean topography, but there are undoubtedly important regions where the errors are larger than this value. The Topex/Poseidon altimetric mission will improve these values by directly observing the tides by taking advantage of their unique but aliased frequencies. In addition to altimeter data, measurements made by existing and future tide gage networks will considerably reduce the tidal errors. The deployment of new tide gages will be undertaken during WOCE, especially in areas where large uncertainties exist, and new methods are being developed to compute tides using altimeter data along with tide gage data (see Le Provost and Fornerino, 1985).

F. The Inverted Barometer

As atmospheric pressure increases and decreases, the sea surface tends to respond hydrostatically. That is, a 1-mbar increase in atmospheric pressure depresses the sea surface by 1.01 cm. This does not apply over times shorter than roughly 2 days (the ocean does not have time to respond) nor over very long periods (about 1 year, where other meteorological effects dominate). Because surface pressure over the sea is not available from space, it must be inferred from wind measurements and analysis of surface observations. Meteorologists estimate that present surface analyses of atmospheric pressure over the sea are generally accurate to ±3 mbars although the error may be much greater in regions such as the South Pacific where there are few ships or in extreme winter storms. This accuracy is expected to improve considerably in the next 5 to 10 years as both meteorological data and our understanding of the atmosphere improve as a result of the Global Weather Experiment and as surface winds become available from satellite-borne scatterometers such as the NASA scatterometer (NSCAT) instrument now being planned for flight on the Navy's NROSS satellite (see section V.C). In any case, the error varies little over distances of hundreds of kilometers and will not overly influence measurements of the short-wavelength oceanic topography. For longer wavelength features, surface pressure with an accuracy of around ±3 mbar will be obtained from the Fleet Numerical Oceanographic Center and from the European Center for Medium Range Weather Forecasting at Reading, U.K.; and the pressure information will be incorporated into the Topex/Poseidon data records.

Section IV
Topex/Poseidon: The Ocean Topography Experiment

The major goal of Topex/Poseidon is to improve substantially our understanding of the ocean's circulation and its fluctuations. Considered as a purely scientific endeavor, this goal is of great importance by itself, for it will provide the first comprehensive, global insight into ocean dynamics. Beyond this lies a wide range of other important benefits. In part, these benefits stem directly from an improved understanding of the ocean circulation; in part they are a by-product of data collected for the experiment.

Improvements in the understanding of ocean circulation contribute directly toward the goals of the World Climate Research Program, especially to such experiments as the World Ocean Circulation Experiment (WOCE) and the Tropical Oceans and Global Atmosphere (TOGA) Experiment (see Section V). Topex/Poseidon will be an important element of these global experiments. By combining Topex/Poseidon measurements with internal measurements of the ocean being planned as part of these experiments and by incorporating these measurements into new computer models of the ocean circulation, it will be possible for the first time to understand the major elements of the global circulation of the oceans and their interaction with the atmosphere.

This section and the next present an outline of (1) the general concept for an ocean topography experiment to measure the surface geostrophic currents and their variability from the mesoscale to global scales over periods from months to years; (2) the auxiliary experiments that might appreciably benefit from the satellite data, and (3) the relationship of Topex/Poseidon to the other elements of the World Climate Research Program. Of course, the scope and elements of an Ocean Topography Experiment remain to be defined in a Science Plan. This will be written by the Principal Investigators chosen through the NASA and CNES coordinated Announcements of Opportunity.

A. Ocean-Circulation Experiments

A determination of the general circulation of the oceans has been a goal from the very beginning of oceanography, attracting the attention of Benjamin Franklin in the 18th century and Alexander Dallas Bache and Matthew Fontaine Maury of the U.S. Coast Survey and of the Navy, respectively, in the 19th century. The general circulation is, loosely speaking, the large-scale, time-averaged movement of water. The ocean is a global fluid with large variability both regionally and temporally, and it contains different dynamic and kinematic regimes, much as the atmosphere does. Superimposed on the time-averaged flows are a variety of time-dependent processes, and these render the determination of the average extremely difficult. These time-dependent processes also contribute dynamically to the large-scale mean distribution of properties.

From the past decade of work, it is known that over great areas of the ocean, the mesoscale variability or eddies can have energy levels one or more orders of magnitude greater than that of the mean flow (Fig. 16). Through eddy Reynolds' stresses, the field of variability is capable of generating the time-averaged movement of various fields, including passive tracers such as tritium, dynamically active tracers such as heat and salt, and dynamical quantities such as momentum and energy. Because these different properties of the water can be transmitted and mixed differently, the general circulation of the ocean cannot be defined uniquely. The definition of the circulation depends on the property that is studied.

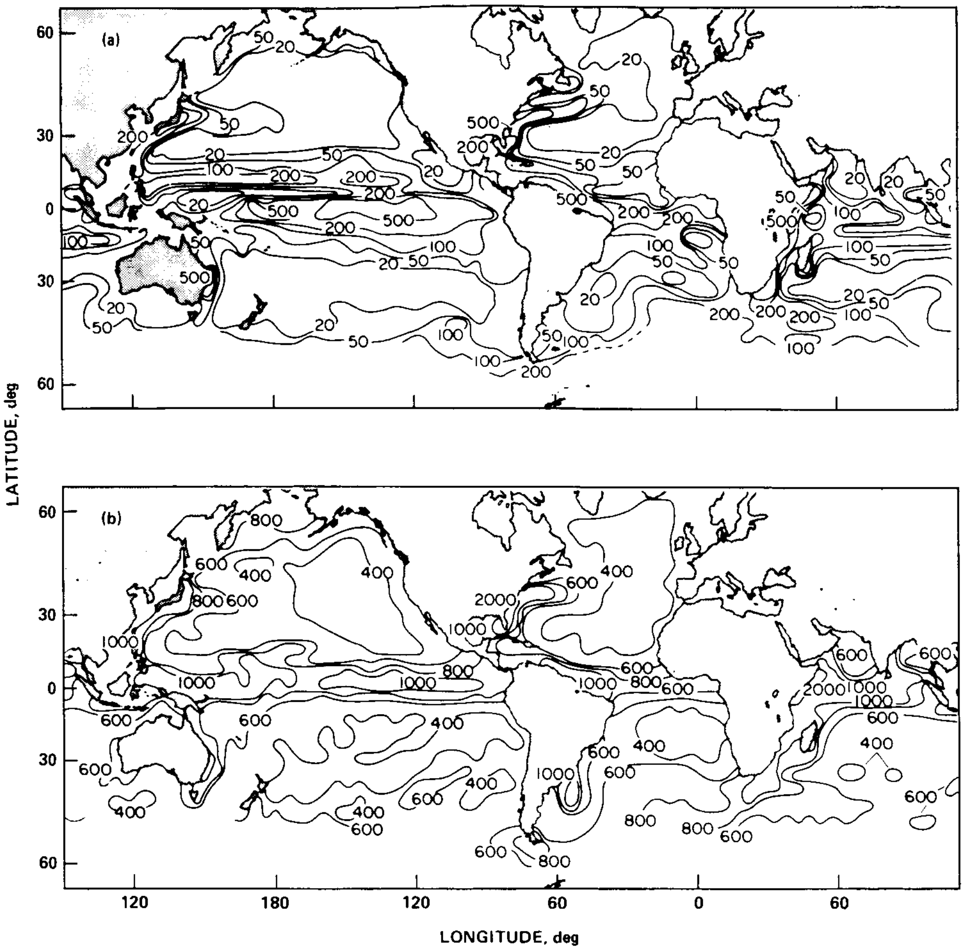

Fig. 16. Mean and variable kinetic energy of surface geostrophic currents: (a) per unit mass of the mean surface flow based on 5-deg square averages; (b) eddy kinetic energy of the surface per unit mass based on 5-deg square averages. Note that the variable flow tends to have considerably greater energy than the mean (after Wyrtki, et al., 1976).

An important component of the circulation in the surface layers of the ocean, the surface geostrophic current, is directly related to the ocean topography, the level of the sea relative to the geoid (cf. Fig. 1). Sea level relative to the center of the Earth can be measured by a radar altimeter from space. If the geoid relative to the center of the Earth is known, then the surface geostrophic currents can be readily computed from the difference between sea level and the geoid. The Ocean Topography Experiment, using altimeter data from the Topex/Poseidon satellite, is designed to investigate the dynamics of surface currents, their variability, their relationship to wind and thermal forcing, and their role in climate.

1. Geostrophic Currents and Topography

Generally speaking, water movements having spatial scales greater than about 30 km and time scales longer than about a day are in geostrophic balance to a very good first approximation. According to this approximation, the Coriolis force resulting from water movement balances the pressure gradient due to a slope in the oceanic topography (Fig. 17). Thus water movement tends to be around highs and lows of the pressure field. The pressure field in the ocean manifests itself as a slope of the constant-density surfaces (isopycnals) in the sea relative to level (geopotential) surfaces.

Most large-scale motion in the sea is what oceanographers term "quasi-geostrophic," meaning simply that the motion is not perfectly geostrophic. Perfect geostrophic balance does not permit any time evolution of the field and does not allow any forces to act, implying that there are no sources or sinks of energy and momentum. But both in theory and practice, the deviations from geostrophy required to produce the neces-

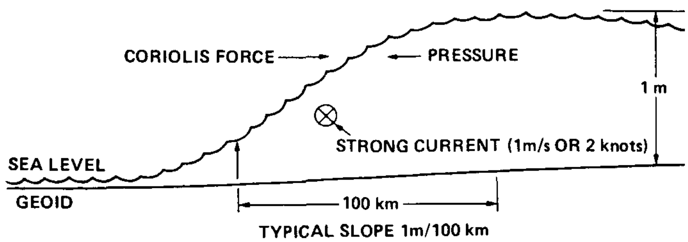

Fig. 17. The slope of the sea level relative to the geoid is directly proportional to surface geostrophic current when the current is in geostrophic balance. A slope of 1 m in 100 km at mid-latitude is due to a current of roughly 1 m/s.

sary fluxes of energy and momentum are very small and not normally observable by *direct* measurement.

Given the assumption of geostrophic balance, oceanographers proceed to determine ocean currents as follows. The statement that the ocean is nearly in both geostrophic balance and hydrostatic equilibrium is expressed mathematically (in local Cartesian coordinates) by

$$fv = \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad (1)$$

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} \qquad (2)$$

$$0 = \frac{\partial p}{\partial z} + g\rho \qquad (3)$$

where $f = 2\Omega \sin(\theta)$ is the Coriolis parameter, θ is latitude, Ω is the rotation rate of the Earth, x is the east-west coordinate, y is the north-south coordinate, g is the local gravity, p is pressure, ρ is density, z is the vertical coordinate, v is the y component velocity, and u is the x component velocity. Let us focus on v. We can combine Eqs. (1–3) to give

$$v(x, z) = \frac{g}{f}\int_{z_0}^{z} \frac{1}{\rho}\frac{\partial \rho}{\partial x}\, dz + v_0(x) \qquad (4)$$

where v_0 is an unknown constant of integration dependent upon the arbitrary depth z_0 (reference level) from which the integral is begun. By using temperature and salinity measurements from ships and an equation of state, oceanographers compute the first term of Eq. (4), often called the *relative velocity* or *thermal wind*. The constant of integration (reference velocity) is normally unknown, although a measurement of v at any depth z for a given x fixes v_0.

For example, if the surface velocity $v_s(x)$ were known, the reference level z_0 could be chosen to be the surface $z_0 = 0$, and we would thus have

$$v(x, z) = \frac{g}{f}\int_{0}^{z} \frac{1}{\rho}\frac{\partial \rho}{\partial x}\, dz + v_s(x) \qquad (5)$$

But the surface velocity may be written as

$$v_s(x) = \frac{g}{f}\frac{\partial \zeta}{\partial x} \qquad (6)$$

where ζ is sea level relative to the geoid. Thus, a measurement of the slope of the sea surface can determine the surface geostrophic velocity, from which the geostrophic velocity at depths can be determined if the velocity relative to the surface or the internal density field is also known.

In the past, the ocean topography was usually computed under the ad hoc assumption that a deep surface of constant pressure coincides with an equipotential gravity surface. Figure 18, after Wyrtki (1975, 1979) who used the 1000 decibar surface as a reference level, is typical of the kind of ocean topography built up over the past 100 years by shipborne oceanography. As noted above, the errors in such a map due to the deviations of the reference level from an equipotential surface can be greatly reduced by the observations from Topex/Poseidon.

2. Deviations From Geostrophy

The ocean differs from geostrophic balance in a number of ways, and it is useful to have some understanding of how this occurs. The most obvious demonstration of deviations from pure geostrophy in the open sea is the evolution of the velocity field with time, implying that there are missing time-dependent terms in momentum Eqs. (1) and (2). But it is still true that at any particular time the balance is dominated by the Coriolis and pressure forces, with the missing acceleration terms being a small residual.

There is other evidence that nongeostrophic balances exist for some restricted circumstances. In regions like the high-speed core of the Gulf Stream, the *downstream* balance tends to be measurably nongeostrophic. For example, it is possible to observe the Bernoulli head (the Gulf Stream flows downhill) along the coast of the United States (e.g., Sturges, 1974). This is a manifestation of missing nonlinear terms in the momentum equations. Theory (Charney, 1955) also requires them. But it remains true that the cross-stream balance, involving the Coriolis force from the dominant downstream flow remains geostrophic to high order.

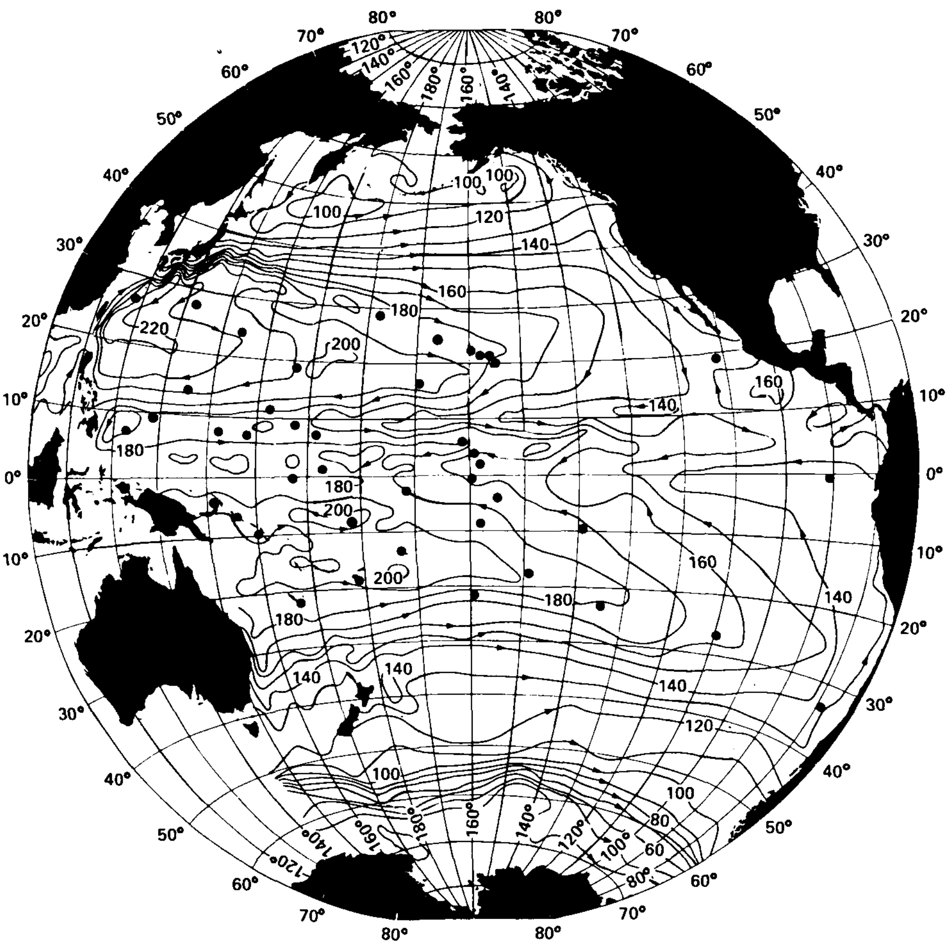

Fig. 18. Sea-surface topography computed under the assumption that the 1000-decibar pressure level coincides with a gravitational equipotential surface. The large dots denote the position of existing tide gages in the Pacific network (after Wyrtki, 1979).

Another region where geostrophy is not expected to apply at first order is in the immediate vicinity of the equator, where the Coriolis force vanishes. But geostrophy does apply to a surprisingly low latitude (2 or 3 deg), although the observational accuracy required to make use of it increases considerably. Right on the equator where the Coriolis force vanishes, the pressure force is balanced by nonlinear (or time-dependent) terms in the equations of motion. The pressure force can, of course, be used in the equations of motion to infer the velocity field as is done with geostrophy, although the relationship is more complex. Hence the equatorial region has a somewhat different dynamical balance governing the strongly time-dependent flows and must be treated as a special region.

On short time scales there are other important flows which produce changes in sea level but which are not in geostrophic balance. Among these are tsunamis (which are long gravity waves), storm surges, and tides. Storm surges are a shallow water phenomenon. Tsunamis are short-lived and also of significant amplitude only in shallow water. Tides are important and are discussed in Section IV.C.1.

In regions where the ocean is directly forced, geostrophy also does not apply. The ocean circulation is driven at the sea surface by two forces, the wind stress and the buoyancy resulting from radiation and the exchange of heat with the overlying atmosphere. With the exception of a few small, localized (but extremely important) regions of deep thermal convection, the coupling of the atmosphere and the ocean occurs in a thin surface layer approximately 100 m thick. This boundary layer is nongeostrophic, but the pressure gradients within it are directly related to the geostrophic flow beneath. Because the oceanic circulation and its variability will only be understood completely when the forces acting at the surface are understood as well, the Topex/Poseidon satellite is designed to fly at the same time as the NROSS and ERS-1 satellites, both of which carry scatterometers to measure the wind field at the sea surface.

3. Oceanic Variability

The turbulent nature of ocean currents, their global extent, their regional and temporal variability, and the interrelationship among all scales of motion greatly complicate studies of the circulation. The temporal variability of the ocean has been measured at a variety of locations in the ocean, particularly in the North Atlantic. Figure 19 displays the frequency spectra from 1-yr-long current-meter measurements in the mid-North Atlantic. They are reasonably typical of open-ocean spectra in being quite "red"; that is, the energy density increases with decreasing frequency. The redness has two important consequences:

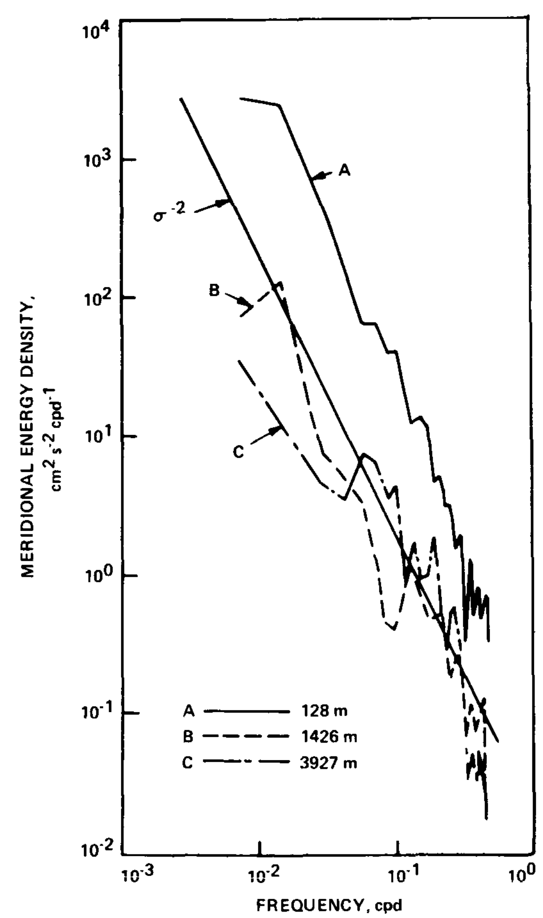

Fig. 19. Typical frequency spectra of the north-south component of velocity in the central North Atlantic (27°25′N, 41°08′W) measured by moored current meters (after Wunsch, 1981a)

(1) A 1-yr record is insufficient to determine a weak mean, i.e., time-averaged flow. The 1-yr average velocity of the record at 128 m is 18 cm/s and is not statistically significant. Thus the duration of a mission to determine the time-averaged ocean circulation at a point is several years at least.

(2) The nearly −2 slope of the spectrum at high frequencies implies that altimeter measurements of current will have important aliases only near the Nyquist frequency of the measurements (see Wunsch, 1972).

The spectrum of longer-term variability in the western North Atlantic (Fig. 20) shows a flattening, or plateau, occurring at around 100 days, a feature that corresponds to the mesoscale eddy field studied by the MODE Group (1978), and others. Deeper in the ocean, the spectrum tends to increase much less steeply toward lower frequencies.

The vertical structure of the motion tends to be dominated by the lowest modes, that is, by the barotropic mode (having velocity independent of depth with no signature in the density field) and the first baroclinic mode (having one reversal in direction with depth in the horizontal velocity) with a strong density signature appearing as a gross movement up or down of the main thermocline.

The spatial variability of the ocean is less well known. Most of the data (e.g., Bernstein and White, 1974; Wunsch and Gaposchkin, 1980) suggest a nearly white velocity spectrum at scales larger than the Rossby radius of deformation (for its definition see Pedlosky, 1979, p. 9.), with possibly an excess at wavelengths around 200 km, corresponding to the mesoscale eddy field (also see Menard, 1983 and Fu, 1983b). It may be true that at sufficiently small wave numbers the motions become more steady and dominated by the time-mean circulation which has a definite tendency to be zonal, i.e., is parallel to lines of constant latitude (Rhines, 1977).

By combining the general observations on temporal and spatial variability, we can sketch (Fig. 21) the outline of the frequency-wave-number spectrum of the general circulation of the ocean, a sketch that will be useful for the following discussion of strategies for sampling the ocean. The peak near 100 days and 100 km is due to mesoscale eddies, and the ridge at one year is the annual variability that can be found at many wavelengths. Little variability is expected at scales smaller than the Rossby radius of deformation or at high frequencies, but considerable variability is expected at long periods. All these sweeping generalities must be modified in detail in the presence of bottom topography, proximity to strong mean flows, and oceanic boundaries. In the vicinity of the Gulf Stream (and by inference the Kuroshio and other western boundary currents),

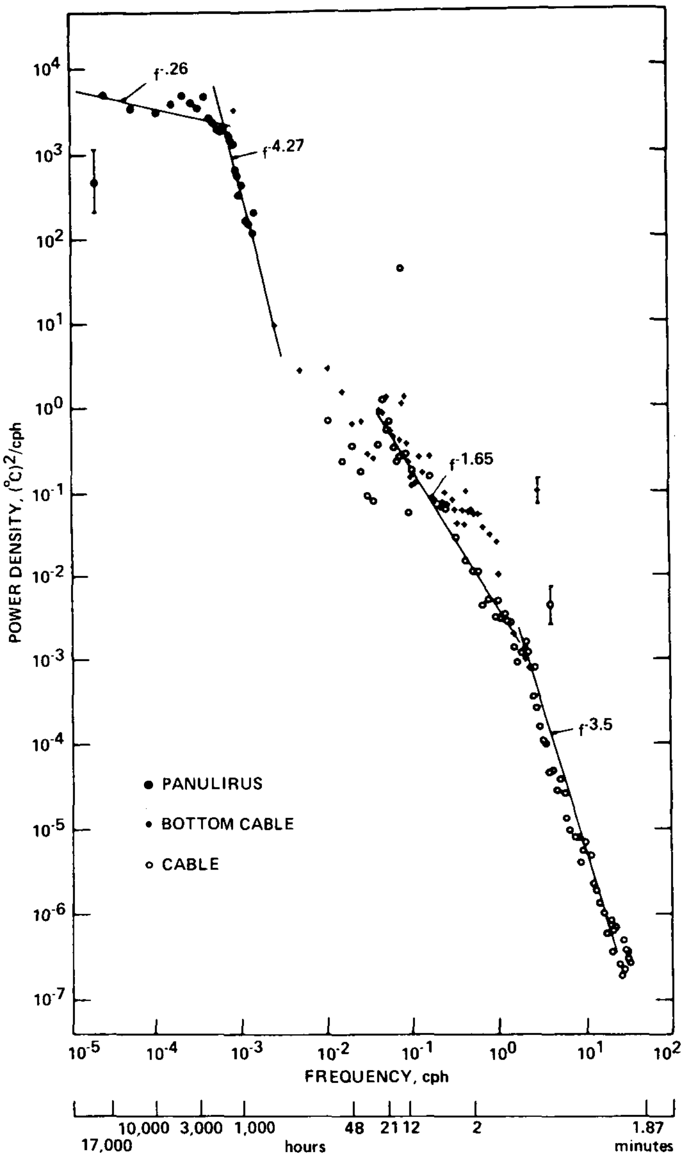

Fig. 20. Frequency spectrum of variability of temperature in the main thermocline near Bermuda. Note that the variance is due almost entirely to fluctuations with periods greater than 40 days and that the spectrum tends to be flat at these periods (after Wunsch, 1972).

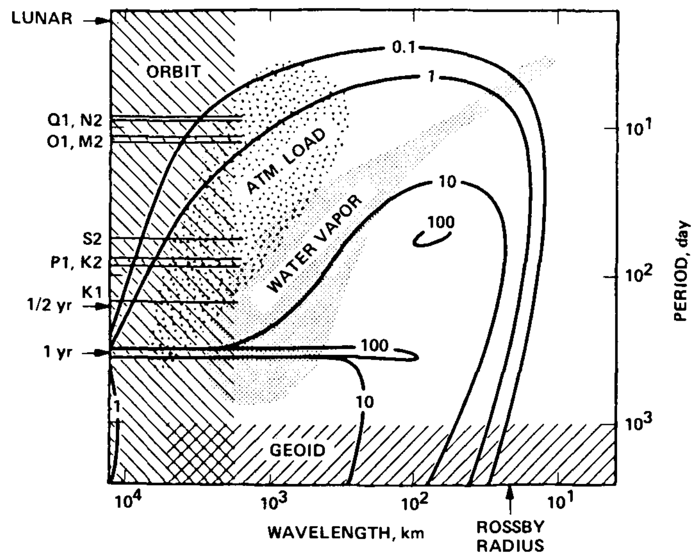

Fig. 21. Sketch of the frequency-wave-number spectrum of the general circulation at mid-latitudes, with arbitrary contour units (after NASA, 1981)

the eddy band becomes considerably more intense and tends to shift toward somewhat shorter periods (about 50 days; Schmitz, 1978). When strong currents are channeled, e.g., the Florida Current (Duing and Mooers, 1977) or the Antarctic Circumpolar Current through the Drake Passage (Nowlin, et al., 1981), the spectra have strong motions at periods of 3–20 days. On the equator (Wunsch and Gill, 1976) velocity and hence sea level also tend to have considerable energy at periods between 2 and 30 days. These special regions are, in terms of geographical area, a small fraction of the world ocean, but they are kinematically and dynamically important.

4. Measuring the Variable Ocean Circulation

Altimeter measurements of variable geostrophic currents do not depend critically on an accurate geoid. Thus these currents are more easily measured than the mean currents, which depend on a partition of sea level into a component due to the geoid and a component due to a mean current. If the ground track of the altimeter exactly repeats, then any difference in repeated altimetric measurements must be ascribed to changes in oceanic currents, apart from those due to tides, atmospheric pressure loading, and residual errors of measurement. Some knowledge of the gravity field is still required for the determination of the variability of currents over large distances, but only because this determination depends upon an accurate ephemeris, which requires accurate knowledge of gravity.

The utility of satellite altimetry in detecting temporal variabilities of ocean currents has been demonstrated by many investigators (see Fu, 1983a for a review). Displayed in Fig. 22 is a map of the global mesoscale variability derived from one month's Seasat repeat-track altimeter data (from Cheney, et al., 1983). Note its similarity to Fig. 16, which is obtained using seventy years' of ship-drift data. Daniault and Menard (1985) have also demonstrated good agreement between kinetic energy of the currents in the southern ocean calculated from Seasat altimeter data and that measured by drifting buoys deployed during the First Global GARP Atmospheric Experiment (FGGE). In addition to its contributions to the study of mesoscale variability, altimetry is also useful for observing the variability of larger scale motion. Fu and Chelton

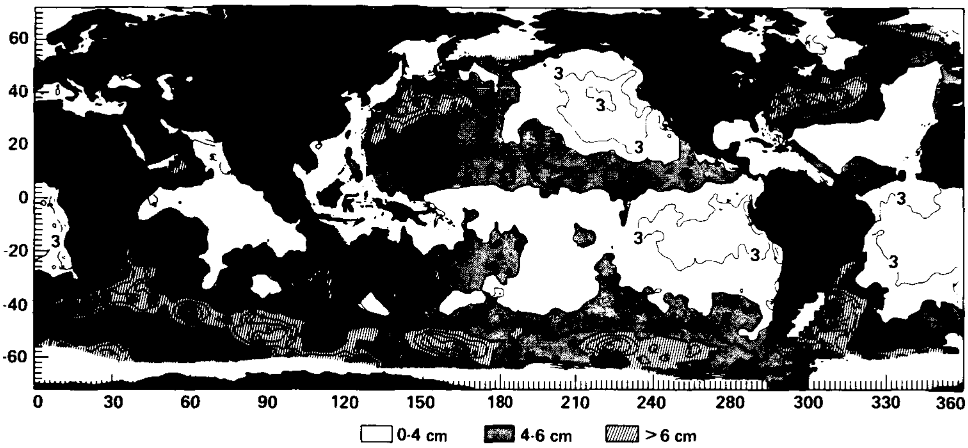

Fig. 22. Sea surface height variability from the repeat tracks of Seasat altimeter data. Contour interval is 1 cm (after Cheney, et al., 1983)

(1985) have detected global-scale variations in surface velocity of the Antarctic Circumpolar Current (Fig. 23) using Seasat altimeter data.

The short life of Seasat, its inadequate sampling scheme, and its limited accuracy compromised the scientific utility of Seasat data. To make quantitative use of satellite altimetry to improve substantially our knowledge of the variability of the global ocean, a better sampling scheme and better measurement accuracy are required.

a. Sampling considerations. We need to consider the sampling requirement both in space and in time. We first consider sampling in time. As noted above (Fig. 19), the slope of the frequency spectrum of mid-ocean temporal variability at periods shorter than the mesoscale is sufficiently steep that important aliases caused by sparse sampling will occur only near the Nyquist frequency of the measurement. Thus, to measure the mid-ocean temporal variability, a sampling interval as long as 25 days could be tolerated.

The temporal variability in regions of strong boundary currents, also as noted above, is somewhat different from that in the mid-ocean. It tends to have shortened periods and often considerably intensified energy levels. Hence the sampling strategy required for these important regions is different from that for the mid-ocean.

It is not possible for a single spacecraft to cover completely the full spectrum of variability everywhere in the world ocean. For instance, to sample adequately regions with 3-day variability would require ground tracks that repeat every 1.5 days or sooner; this would greatly reduce the available geographical coverage by a single spacecraft. That is, the temporal sampling interval must be traded against the density of subsatellite tracks. A reasonable compromise is a basic 10-day sampling strategy. Samples made at this interval have a Nyquist frequency of 1 cycle per 20 days, which should be adequate for more than 90% of the global ocean, and a track separation of 316 km at the equator (see Fig. 2). Nevertheless, the Topex/Poseidon mission has been planned so that the repeat period can be any value between 3 and 20 days, and it can be changed

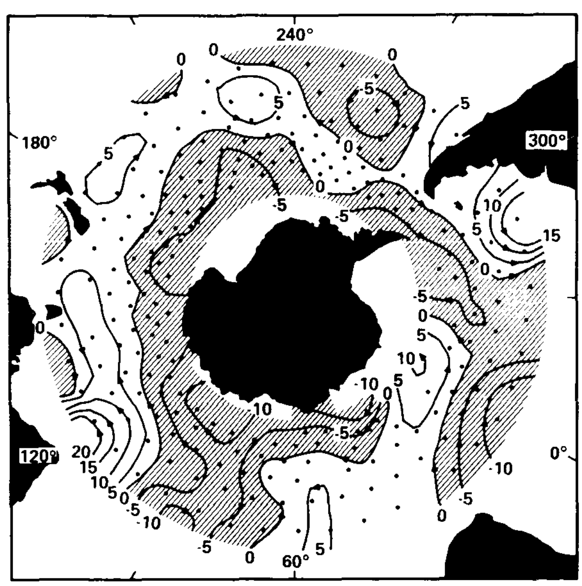

Fig. 23. Low-frequency (periods longer than 20 days) sea level changes measured by the Seasat altimeter over the southern ocean between 40-deg and 65-deg south from 12 July to 11 October 1978 (October minus July). The directions of the corresponding change in surface geostrophic velocity are indicated by the arrows. The dots designate the locations of the altimeter observations.

once after launch to another value in this range. Thus the Principal Investigators can consider the usefulness of two different sampling rates at different phases of the experiment. For the present, we will assume a fixed orbit repeating every 10 days.

The 10-day coverage implies that the altimeter will be used to map the variability field in spectral terms rather than in physical space. As can be seen from Figs. 2 and 3, only features larger than the basic size of the "diamond" pattern could be contoured. Scales smaller than this will be well determined in the along-track directions down to a spatial scale of the order of the system resolution (basically the footprint size) of about 10 km.

For purposes of studying the variability, it is often said that a good geoid is unnecessary. This is only true if the ground tracks repeat exactly so that subtraction of successive altimetric measurements removes the unknown geoid. If successive tracks are offset, then different parts of the geoid will have been sampled, introducing a spurious signal into the difference between successive altimetric measurements. To alleviate this problem, the Topex/Poseidon orbit will repeat within ±1 km, which will make the geoid contamination insignificant over most of the oceans (see Fu, 1983b).

Apart from the ice-covered Arctic Sea, oceanic areas at high latitudes include the southern ocean close to the Antarctic Continent and the Norwegian Sea. To fully cover the southern ocean requires an orbit with an inclination greater than about 70 deg. On the other hand, low-inclination orbits are required to provide subsatellite tracks that cross at high angles so that both components of the geostrophic velocity can be adequately measured. The best compromise is an inclination of about 63 deg (see Section II.C).

The Topex/Poseidon mission is planned to coincide with the ERS-1 mission (see Section V.D). The altimeter on this satellite can be used to observe the ocean between 63 deg and 80 deg. At lower latitudes, the additional coverage provided by this satellite, when combined with that of Topex/Poseidon data, would greatly improve our ability to map the global mesoscale variability. Although the ERS-1 altimeter is less accurate than that of Topex/Poseidon, the altimeter data of the latter can be used to improve substantially the ephemerides of the former, and the Topex/Poseidon measurements of total electron content and water vapor may prove useful for correcting the ERS-1 altimeter data.

b. Accuracies. The accuracy required of an altimetric system is a complex function of space, time, and region, and it must ultimately be determined by what is asked of the data. A few guideposts are available.

The variability in the immediate vicinity of strong western boundary currents contains meanders and eddies with variations in sea level of nearly one meter over distances of several hundred kilometers. These disturbances have been measured even with the comparatively crude Geos-3 altimeter system (Huang, et al., 1978) and have been observed very clearly by Seasat (Cheney and Marsh, 1981a). To map and track the changes in sea level of western boundary currents with an accuracy of 5% requires a system with a 5-cm precision over distances on the order of 50 to 500 km. This was achieved by Seasat.

Seasonal and interannual fluctuations of the ocean circulation produce much smaller variations in sea level than do eddies near boundary currents. One of the few observations available is that the range of seasonal variability of the total transport through the Florida Straits by the Gulf Stream is $\sim 8 \times 10^6$ m^3/s (Niiler and Richardson, 1973) which corresponds to a change in head across the 100 km of the Florida Straits of about 12 cm. In other regions, the variability is considerably less, being on the order of 5 to 10 cm.

How accurately could a 10-cm change be determined? Assume, based on the Topex/Poseidon error budget (Table 2), that for any particular pass the standard deviation of error in the sea-level measurement is about 14 cm. In practice, the passes will be used to form a surface computed by a crossing-arc analysis (e.g., Rapp, 1978; Marsh, et al., 1980) or some other procedures (e.g., Wunsch and Zlotnicki, 1984). The accuracy with which the slope of the surface can be found should be significantly better than the accuracy of the slope computed from any single pass. By extrapolating from the results of Wunsch and Zlotnicki (1984), who studied the accuracy of the altimetric surface based on Seasat error statistics, we can estimate the accuracy of an altimetric surface constructed over a region of 5000 $\times$ 5000 km (roughly the size of the mid-latitude North Atlantic) using 10 days of Topex/Poseidon data (with 14-cm accuracy) as 3.5 cm. In a period of 6 months, during which 18 independent surfaces are obtained, the error for a 6-month mean surface is then reduced to 0.9 cm. According to Wunsch and Zlotnicki (1984), if any single arc can be tracked with an accuracy better than the estimated 14-cm orbit error, the accuracy of the surface can be further improved.

5. Measuring the Permanent Ocean Circulation

The ocean fluctuates on all time scales. For present purposes and to avoid semantic difficulties, we will refer to the permanent circulation as that given by a 3-yr time average. This circulation is thought to contain all spatial scales from the Rossby radius of deformation (Pedlosky, 1979, p. 9) – about 30 km – to the dimensions of the largest ocean basin. A determination of the corresponding time-averaged geostrophic

ORIGINAL PAGE IS
OF POOR QUALITY

velocity field is more difficult than that of the time-variable part because the marine geoid must be known with high accuracy. Measurements from the proposed Geopotential Research Mission and/or the Gradio Mission (see Section III.D) should yield a geoid with an accuracy comparable to that of the altimeter data for wavelengths greater than a few hundred kilometers, although not at shorter scales. In addition, the ocean is a turbulent fluid in which the different spatial scales of flow are coupled together, both kinematically and dynamically. This means that the determination of one range of scales of flow by direct means can strongly constrain flows on other scales that are not directly observed.

a. Accuracies and resolution. Present uncertainties in the time-averaged general circulation translate into elevation variations of up to 25 cm in some areas of strong flows and are probably in the neighborhood of 10 cm or less over more quiescent regions of the interior oceans (see Wunsch, 1981a; Stommel, et al., 1978). The simple statistical arguments used for the variability also suggest that accuracies of this order can be attained in the altimetric system with comparably short averaging times, on all the spatial scales of relevance. But, for the time averages, particularly over the longer distances, it is the systematic errors (see Tapley and Rosborough, 1985) that will dominate, not the random errors that can be removed by crossing-arc techniques. (For the variability, the systematic errors will tend to cancel by subtraction.) The Topex Precision Orbit Determination Group has concluded that the residual systematic error should be no greater than 5 cm in any particular orbit. This value, which may actually be high, is the sum of the residual gravity field uncertainties plus systematic uncertainties in the influence of radiation pressure. The 5-cm level is below the existing level of uncertainty in the ocean topography (Wunsch, 1981b).

The major difficulty in designing an altimetric mission for studying the permanent circulation lies in solving the geoid problem. The errors in existing geoid models are characterized by a blue spectrum, i.e., the largest errors occur in the shortest wavelength and the smallest errors occur in the longest wavelength. Thus if we assume very accurate altimetry is obtained from a multi-year average, then the error introduced into surface geostrophic velocities, and thus into water transports, by the geoid will clearly be minimal on the very longest spatial scales and will grow with shorter scales. Assume that there is a wave number k_c where the error in the surface geostrophic velocity becomes so large that it is not useful. This results in a statement that the surface geostrophic velocity and hence water transport are known in a low wave-number bandpass, $0 < k < k_c$. Is this useful and how does it depend upon k_c?

Using the three months of Seasat data and the GEML2 geoid, Tai and Wunsch (1984) produced a topographic map of the world ocean (Fig. 24). To the extent of the accuracy of the geoid (see Section III.D), they found that the wavenumber cutoff $k_c = 2\pi/6700\ \mathrm{km}^{-1}$, corresponding to spherical harmonics of degree and order 6. Note the qualitative similarity between the hydrography-derived topography and the altimetry result.

The geoid discussion (Section III.D) suggests that with a special purpose Geopotential Research Mission, $k_c = 2\pi/200$ km globally, with an error in sea level of 1.5 cm, corresponding to surface velocity errors of 2 cm/s. The cutoff k_c can be increased regionally, at this level of error, by shipborne gravity measurements. If k_c is decreased to $2\pi/500$ km, the surface velocity error is considerably less. The question about the desired values for k_c and its corresponding velocity errors must be answered in the context of what is known now about the oceanic general circulation. A formalism for doing this has been constructed by Wunsch and Gaposchkin (1980) and by Marshall (1985).

b. Duration. Many of the direct observations made over the past decade (e.g., the MODE Group, 1978) suggest that

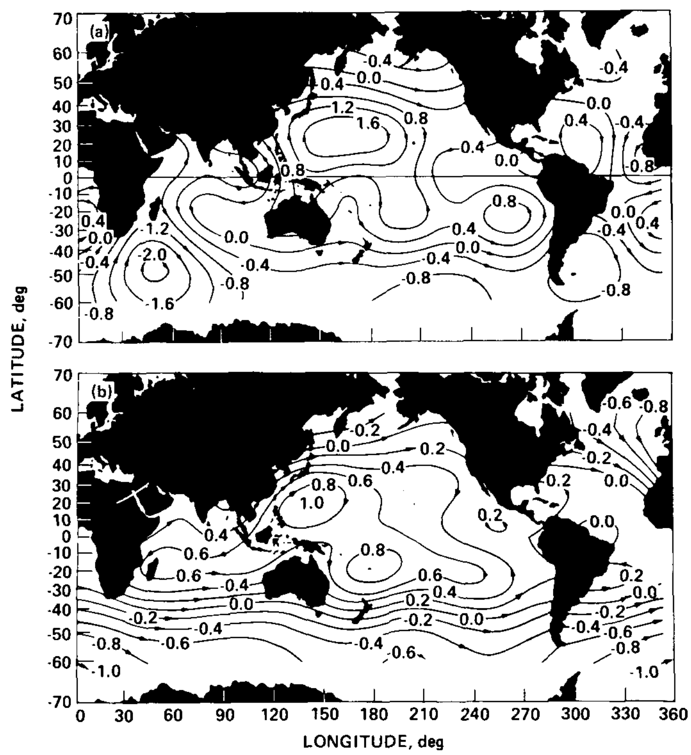

Fig. 24. World ocean topography (in meters) from altimetry and hydrography: (a) obtained from the Seasat altimeter data; (b) topography relative to the 2000-decibar level obtained from shipboard hydrographic data. Both maps are low-pass filtered to retain spherical harmonics up to degree and order 6 (after Tai and Wunsch, 1984).

long-term averages are required to find the mean flows in the presence of strong variability – typically over two or more years in many locations. A mission lifetime of about three years represents a reasonable compromise between the need to have very long averages for stable statistics of both the mean and variable currents and the increased costs of long missions. A 3-yr mission will permit a 3-yr averaging interval that is longer than most extant in situ observations, good determinations of the annual cycle (which are of very great interest both dynamically and climatologically), good first determinations of the interannual variability of the seasonal cycle from year to year, and highly stable statistics of the shorter-than-annual variability. Cartwright (private communication, 1980) has shown that the 3-yr lifetime will permit a determination of tides from the altimeter data, a determination that will vastly improve our knowledge of global tides (see Section IV.C.1). This result will be useful for removing the tides as sources of significant error in the determination of the ocean circulation. If the Topex/Poseidon mission lasts for 5 yr, the result would be correspondingly more useful.

6. The Ocean at Depth

An altimeter observes only surface geostrophic velocities. Optimal use of such information requires ways to couple it with other information about the ocean's interior. Because the direct determination of the ocean's interior density and velocity fields from satellites does not seem possible, we envision obtaining such knowledge in at least two distinct ways: (1) from models of ocean dynamics using the surface observations as boundary conditions, or (2) from direct observations made by in situ instruments, especially those deployed as part of the World Climate Research Program (discussed in Section V).

a. Inference from subsurface observations. The preferred strategy for obtaining fields at depth is the direct use of in situ observations such as ships, floats, drifters, and moorings. These platforms are mismatched to the sampling capabilities of satellites. Nonetheless, because the large-scale features in the oceanic circulation seem to change only over very long times, ships can be used for studying the time-averaged large-scale circulation. The picture of the circulation now available in fact has really been built up by treating decades of observations as though they were made simultaneously. The global ship and in situ observational strategy that is expected to be implemented by the international community as part of the World Ocean Circulation Experiment (described in Section V.A) will be especially useful for interpreting the Topex/Poseidon observations and for calculating the deeper circulation. Another promising remote-sensing technique (but not a spaceborne one) is the use of acoustics in the form of tomography as described by Munk and Wunsch (1979). A combination of basin-wide acoustic tomography plus altimetry would provide the complete three-dimensional time-variable velocity, density, and pressure fields (e.g., Munk and Wunsch, 1982). A realistic strategy involves a combination of in situ measurements with the type of direct dynamical modeling envisioned below.

b. Inference from models. Ocean dynamics as currently understood can be used to model the interior ocean with the surface field as boundary conditions. The governing equations for quasi-geostrophic variability, for example, can be expressed as sums of vertical normal modes. The great bulk of the mesoscale variability manifests itself in density as simple vertical movement of the thermocline, although there are quantitative complexities in any given region. Thus, models can be used to explore the implications for the interior ocean from changes at the surface.

Consider first the variability. Recent mesoscale variability experiments have suggested that the velocity in the interior of the ocean tends to change, at least in the band of periods from weeks to months, essentially as the sum of two "modes" (McWilliams, 1976): (1) the barotropic mode, which leaves the mass field unchanged and which has a velocity profile that is independent of depth; and (2) the first baroclinic mode, which moves the thermocline up and down and which has a horizontal velocity profile with one zero crossing at mid-depth (typically at about 1200 m). In regions where these two modes have different characteristic horizontal wave numbers, a best fit to the observed changes in surface velocity (or pressure) can be made, thus determining the changes in density and velocity with depth (these are computed relative to the time averages). Such ideas can be elaborated to account for such variables as bathymetry and mean shears and will have an accuracy directly dependent upon the reliability of assumed models.

For the time-averaged flow, as with the variability, measurements of the surface pressure fields must be translated into useful information about the subsurface fields. Wunsch (1984) has shown that the surface pressure field as measured by an altimeter is a useful substitute for the upper ocean thermal boundary condition required by models of time-averaged circulation. Therefore, altimetry and scatterometry (which measures the wind field at the ocean surface) differ from all other possible measurements from space in that, at least in principle, they directly measure the boundary conditions for the dynamical equations governing the three-dimensional movement of the fluid. In the atmosphere, the specification of the surface fields alone does not provide adequate information for computing the fields at higher elevations; but the ocean differs significantly from the atmosphere in having all of its energy sources at the surface (there is no oceanic analog of radiation absorption at high altitudes).

B. Geophysical Experiments

The Ocean Topography Experiment, although primarily designed for studies of ocean dynamics, will also be useful for geophysical studies as noted in reports by the National Research Council (1978, 1979b); the benefits range from an improved knowledge of the geoid, and hence insight into lithospheric dynamics, to a better understanding of processes deeper in the Earth. Because these geophysical applications are important, they warrant a brief discussion here.

The height of the sea surface relative to the center of the Earth is determined by both ocean dynamics and the geoid. The latter dominates, producing changes in height that are roughly 100 times those due to surface currents, and thus altimetric observations of sea level are useful for the study of the interior of the Earth because the geoid is related to the distribution of mass within the Earth.

Studies of the geoid near seamounts on the ocean floor indicate that the lithosphere behaves as a thin elastic plate riding on top of a more fluid substratum. The plate supports the load of the seamount over distances of a few hundred kilometers, but beyond this distance it bends and the weight of the seamount is balanced by buoyancy forces acting on the plate resulting from its sinking. The compensation is observed by noting the ratio of the strength of the anomalies in the gravity field relative to the bathymetry. For some distances (near 200 km) that are determined by the thickness and strength of the plate, the ratio suddenly becomes small, and this is an indication of the strength of the plate. For shorter distances, the geoid undulations are due primarily to bathymetry, and for greater distances they are due primarily to the distribution of mass below the plate.

1. Oceanic Bathymetry

The lithosphere is relatively rigid over distances of a few hundred kilometers, and changes in sea-floor topography produce corresponding changes in the shape of the geoid (Fig. 25). Subsea mountains and seamounts are particularly prominent, the latter producing changes in elevation of 1–10 m in the geoid over distances of tens of kilometers, and maps of geoid height with resolution of 10–20 km can be used to map the distribution of subsea features.

Maps of seamounts are important to geophysics and oceanography:

(1) The total volume of seamounts is an indication of igneous activity, and they may account for a significant portion of the total production of igneous rocks on Earth.

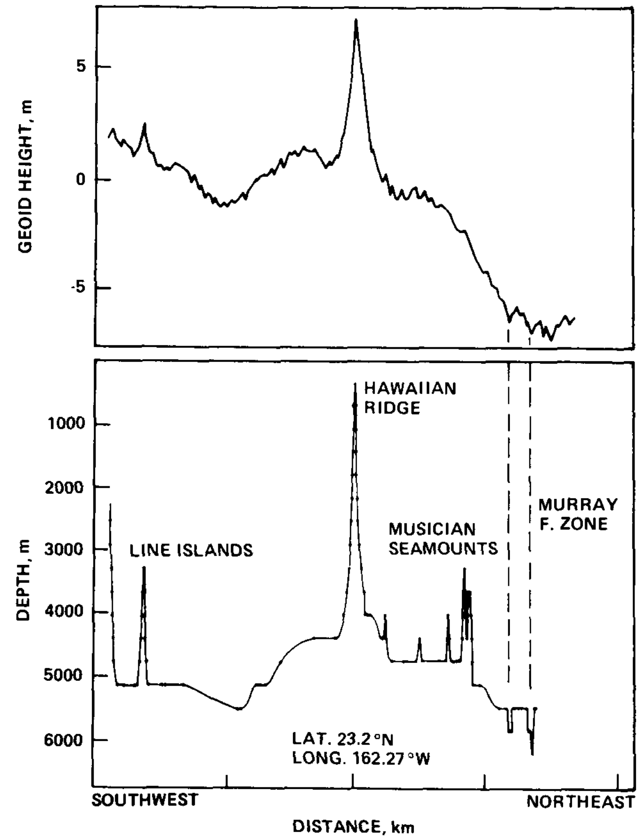

Fig. 25. Height of the geoid measured by an altimeter on Geos-3 and the corresponding bottom topography along the subsatellite track. The geoid profile has had a regional geoid subtracted from it to emphasize the influence of the bottom topography (after Watts, 1979).

(2) Seamounts disturb the flow of ocean currents, producing shifts in the path of the currents and large-amplitude internal waves. The latter influence the propagation of sound in the ocean and probably contribute to mixing between surface and deeper layers.

(3) The uncompensated weight of undersea mountains near ridge crests produces stresses that tend to push the ridge crests apart (Parsons and Richter, 1980) and this may contribute to spreading at ridge crests.

Despite the importance of these bottom features, they have been poorly mapped in many regions. Seamounts in particular are very small, and are not seen except on those rare occasions when a ship happens to pass directly over the mount. While Topex/Poseidon will produce little more information about the bathymetry than is presently available from Seasat, the improved accuracy of the observations will yield somewhat better information about the correlation of sea level and bathymetry, especially for larger wavelength features.

2. Rigidity of the Lithosphere

The rigid lithospheric plates float on the underlying plastic asthenosphere. The plastic yielding of the latter relieves much of the stress that would otherwise exceed the yielding strength of the lithosphere, e.g., as a result of the decrease in centrifugal force that results from the steadily decreasing rotational rate of the Earth or from the weight of mountains.

The oceanic lithosphere differs markedly from the continental lithosphere. The ocean floor is younger and is primarily basaltic and denser than the lighter and older granitic material on continental crust. The oceanic lithosphere is generally thinner, less than 10 km at ocean ridges, increasing in thickness in a regular fashion to less than 100 km at continental margins. The continental lithosphere is more varied in thickness and has deep "roots" under stable interiors that may exceed 100 km in depth. The lower boundary of the lithosphere under mountainous regions is not well known.

The admittance function, relating undulations of the geoid to undulations of bathymetry, is a function of the strength, thickness, and density of the lithospheric plate supporting the weight of bottom features such as seamounts; and the admittance is used to constrain estimates of lithospheric rigidity (Watts, 1979). The problem is under-determined, and solutions using geoid information alone are not unique. When combined with other information (seismic and geochemical) about the lithosphere, the geoid can give useful information about the strength and thermal properties of the lithosphere and its response to loads (e.g., Cazenave, et al., 1982 and 1983).

3. Mantle Convection

More than two-thirds of the Earth's mass is contained in the mantle. Although the mantle is a rigid solid, stiffer than steel, its viscosity is low enough to permit convective flow over geologic time scales under the influence of internal radioactive heating and heat added at the base of the mantle from the core. Mantle convection is necessary to explain the magnitude of heat flow from inside the earth—conductive heat flow is much too small.

Minor lateral variations in seismic properties suggest mantle inhomogeneities, which may be the result of portions of subducted lithospheric plate that have not been resorbed into the mantle. The mantle is also known to be variable with respect to trace elements and radioactive isotopes from analyses of mantle-driven magmas.

Density is controlled primarily by temperature, and the variations in density should produce variations in the height of the geoid (McKenzie, 1977). Certainly the regional features observed in the oceanic geoid must be due to deeper structure below the lithosphere, and they may be related to mantle convection and other processes which could drive lithospheric plates.

4. Geodesy

We expect that geodetic information provided by the Topex/Poseidon precision orbit determination teams working in the U.S. and France will be of fundamental importance to a variety of geodetic studies. The accuracy of the Topex/Poseidon ephemeris will approach one part in 10^8 and will be the most accurate ephemeris ever calculated for a satellite at heights of less than 1500 km. As a result, the Topex/Poseidon mission relies in a fundamental way on geodetic coordinate systems and information derived by the worldwide geodetic community. In return, the work necessary to calculate an accurate ephemeris of the Topex/Poseidon satellite will provide information useful for geodetic studies.

The most important information includes an improved gravity field at satellite heights and perhaps the geoid at sea level, accurate positions of stations used to track the Topex/Poseidon satellite, direct observation of the geocentric oceanic tides from which could be computed the influence of tides on geodetic coordinate systems, improved estimates of the angular momentum of the ocean and its contribution to changes in the length of day, and accurate relationships among the different coordinate systems used to analyze the Topex/Poseidon data.

C. Auxiliary Experiments

The Topex/Poseidon mission, while designed primarily for the Ocean Topography Experiment, will also produce information useful for other geophysical studies. The Topex/Poseidon altimeters can measure variations in sea level due to tides and storm surges and perhaps could be used to profile the shape of continental glaciers and map the topography of plains. Over sloping glacier ice and over land the leading edge of the reflected altimeter pulse is very diffused compared with reflections from the sea, and the altimeter can neither find nor easily track it. The signal-processing circuitry of the altimeter on Topex/Poseidon, however, will allow the instrument to track the height of the satellite over smooth, gently sloping surfaces such as the Greenland ice sheets and the plains of Florida. The reflected altimeter pulse also contains information about the roughness and composition of Earth's surface, information that can be used to deduce wind speed, wave height, the existence of ice cover over the oceans, and the type of snow cover on glaciers. Auxiliary observations are used to correct the altimeter signal by measuring water vapor in the atmosphere and free electrons in the ionosphere (Stewart, 1985). Note however, that except for the measurements listed in Table 3, no work will be done by the Topex/Poseidon projects to verify the usefulness or accuracy of these other measurements.

1. Calculation of Geocentric Oceanic Tides

Tides are periodic motions of the ocean and the Earth at frequencies precisely known from the gravitational forcing of the moon and sun. They arise directly from the gravitational forcing and indirectly from atmospheric tides, solar heating, and land-sea breezes, the latter being known as the radiational tides. For the solid Earth, a distinction is made between that portion of the tide which is directly forced by the gravitational attraction of the moon and sun and that which is due to the flexure of the Earth due to the weight of the ocean tide. Satellite altimeters measure the sum of the ocean tide and the Earth tide.

Although the ocean tide is forced by low-order spherical harmonic perturbations in the gravitational field (dominantly the second spherical harmonic), the result is a wave motion containing shorter scales. Thus the ocean tide is not a bulge following the moon and sun, but rather it is a long wave profoundly modified by the rotation of the Earth and the natural resonances of the ocean basins. Added to this is the relatively small radiational tide which, for example, contributes a few percent to the total tidal signal along the coasts of North America (Zetler, 1971).

In contrast to the oceans, the solid Earth tide responds nearly elastically and closely follows the gravitational forcing. In addition, the solid Earth responds elastically to the ocean loading with a magnitude of about 10% that of the gravitational response. The influence of the ocean loading extends far inland and can be detected over most continental areas. In principle there should also be a lag caused by dissipation in the solid Earth, but it is yet to be measured, partly due to interference from the ocean loading tide.

Tidal signals appear in many geophysical measurements and have many important influences. For oceanography, (1) tidal dissipation could influence the ocean circulation (Hendershott, 1981); and (2) tides couple with Earth's magnetic field to produce variations in Earth's electric field.

For geophysics, a precise knowledge of the ocean tides would allow the structure of the ocean tide to be used as a known function to be convolved with Earth structure. Depending on the intermediate dynamics, the resulting geophysical signal can be used to infer properties of the solid Earth. The tidal signal also appears in measurements of gravity, tilt, and strain, so improved knowledge of the tides will result in more accurate measurements of these quantities.

For astronomy and space physics (see Lambeck, 1980), the tides are an important factor in determining (1) station locations in three dimensions relative to Earth's center; (2) Earth's moment of inertia and hence the length of the day; (3) the secular retardation of the rotation of Earth; (4) the polar motion; (5) satellite positions, both periodic and secular; and (6) the deceleration of the lunar longitude. (Whether or not all of the deceleration can be explained by tidal dissipation is of importance to geophysics and to the history of the evolution of the solar system.)

Observations of tides by coastal gages have been made continuously for hundreds of years. The extrapolations of these measurements to the deep sea were initially empirical, e.g., the M2 charts by Harris (1904) and Dietrich (1944). More recently the tides have been estimated by direct numerical computations (see reviews by Hendershott, 1977 and 1981; Cartwright, 1977; and Schwiderski, 1980). The best of these computations make extensive use of measurements both along the coasts and in the interior of the ocean. Unfortunately, most coastal measurements are in awkward locations for use with deep-sea tidal models. Besides being on the "wrong" side of the continental shelves, coastal measurements are usually taken in bays, estuaries, or up rivers where the tidal signal is strongly disturbed by the intervening shallow water. Even island gages are usually in harbors or lagoons, and lags of as much as one hour are possible between such a gage and the surrounding deep-sea tide. To avoid these problems, the astronomical ocean tide is now measured directly by bottom pressure gages (Cartwright, et al., 1980); however, the distribution of these measurements in the deep ocean is still sparse (Fig. 26). Using a limited amount of Seasat data, Mazzega (1983, 1985) mapped the M2 tide in the Indian Ocean and globally. These maps, although qualitative, are encouraging. By combining data from coastal and deep ocean tides with altimeter measurements of sea level, and by using these data with hydrodynamic models of tides as suggested by Le Provost and Fornerino (1985), it will be possible to obtain a complete description of the main tidal constituents in the deep ocean.

Topex/Poseidon will provide the observations necessary to calculate for the first time all the dominant deep-sea geocentric tides with useful accuracy. The satellite orbit has been chosen to avoid aliasing one tidal frequency into other tidal frequencies, so with time, all tidal constituents should be observable over the grid of subsatellite tracks. The applications of such a set of observations are varied and will depend on the approach chosen by individual Principal Investigators. For example, the tides could be calculated over a grid, then mapped (e.g., Mazzega, 1985), or they could be used with tidal

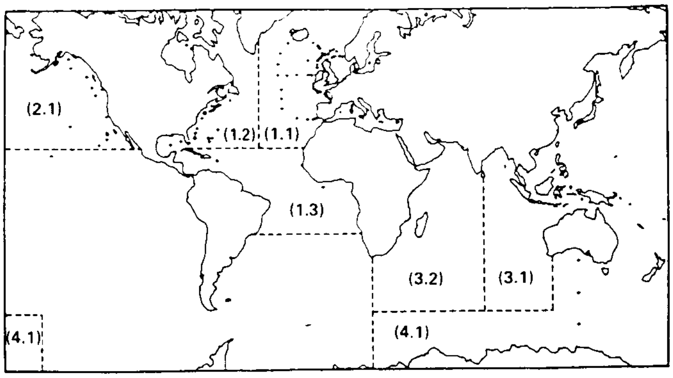

Fig. 26. Global distribution of pelagic tide gage stations compiled by the International Association for the Physical Sciences of the Ocean. Note that the deep ocean tides have been measured in only a few places; hence, our knowledge of tides depends essentially on numerical computations constrained by island and coastal measurements. Since this figure was compiled, a few additional observations have been obtained in the western Indian Ocean and in the Antarctic (after Cartwright, et al., 1979).

models to calculate the admittance of the oceans to tidal forcing. From these studies should come a complete picture of geocentric ocean tides with an accuracy and coverage unavailable from other techniques.

2. Forecasting of Ocean Waves and Storm Surges

The main obstacle in improving our ability to forecast ocean waves is the lack of simultaneous global observations of winds and waves to test wave-prediction models. The measurements of significant wave height and wind speed offered by Topex/Poseidon, when combined with the wind vectors measured by the NASA Scatterometer on NROSS and by the scatterometer on ERS-1, will provide a data base of unprecedented quality and coverage for these tests. The determination of the amplitude and propagation of oceanic swell (Mognard, 1984) is equally possible.

Storm surges, the substantial rises in sea level produced by shoreward storm winds over shallow water in coastal areas, cause flooding, erosion, and damage to coastal structures. The severity of damage is related to the height of the storm surge, which in turn is determined by poorly understood but complex interactions among winds, waves, the phase of the tide, bathymetry, and local currents. The simultaneous measurements of sea level, wave height, and wind speed by Topex/Poseidon, when combined with existing bathymetric information and analyses of storm winds, will have great potential for improving our ability to predict storm surges. Unfortunately, storm surges are rare, and only a few are likely to be observed by the Topex/Poseidon mission.

3. Interaction of Waves and Currents

Ocean waves propagating into regions of opposing currents and into shallow water are shortened and steepened. Typically this is of only minor importance and occurs in coastal areas where incoming waves meet shoals and locally strong tidal currents. But in a few regions, waves of much greater importance are produced. Along the east coast of South Africa, the southward flowing Agulhas Current meets large storm waves coming up from the southern ocean, steepening and focusing them. Both influences combine to produce monster waves capable of severely damaging or sinking large supertankers (Dawson, 1977). One such wave caused $1,200,000 damage to the tanker *Wilstar* (132,700 tons) in 1974, while another sank the *World Glory* (48,823 tons) in 1968 (Mariner's Weather Log, 1974). Other monster waves have been recorded along the Greenland continental shelf, along the north edge of the Gulf Stream, near Ushant at the approach to the English Channel, and off the northwest coast of India.

The regions where giant waves occur and the general conditions producing such waves are known and described in the appropriate "Pilots," but the exact mechanisms are not understood well enough to predict accurately the occurrence of the waves. In particular, the relative importance of bathymetry and currents in influencing long, steep waves remains to be determined. Further investigations will require detailed observations of waves and currents over scales of 100–1000 wavelengths (20–200 km) for use with existing theories of wave-current interactions. Especially needed are velocity profiles, maps of bathymetry, and observations of wave heights across the particular current system at the times they encounter long steep waves. Topex/Poseidon offers simultaneous measurement of current and wave height for these studies.

4. Ocean Currents and the Earth's Angular Momentum Budget

Changes in the distribution and circulation of water in the ocean will cause fluctuations in the length of day by changing the net angular momentum of the oceans about the polar axis. Although changes in the angular momentum of the atmosphere drive most of the fluctuations in the length of day over times of a year or less, the residual is now known well enough to investigate the role of the ocean in the terrestrial angular momentum budget. This investigation is obscured by possible systematic errors in the angular momentum budget and by the lack of reliable estimates of the oceanic angular momentum. While estimates of atmospheric momentum are directly available from the atmospheric models used in weather forecasting, similar oceanic estimates are currently not available. Topex/Poseidon offers the opportunity to directly estimate the oceanic angular momentum from radar altimetry and some in situ observations. These estimates could be used to explore the interchange of angular momentum among the ocean, atmosphere and solid Earth.

5. Fisheries

The ocean has been fished for food since prehistoric times and today provides a large fraction of the world's food supply. Yet only a few very limited regions of the ocean can sustain important fisheries (The Grand Banks, the coast of Peru, and the Gulf of Alaska, for example), primarily because of the special oceanic flows required for high productivity. These special environments are often fragile, waxing and waning in ways as yet unpredictable (the Peruvian and California anchovy fisheries are prime examples); and the conditions that lead to particularly good fishing at one time and place and not at another are usually determined by oceanographic and meteorological conditions on a much broader scale. Topex/Poseidon will monitor these conditions on a global basis and provide potentially useful information for the world's fisheries.

6. Earth's Ionosphere

The dual-frequency (13.6 GHz and 5.3 GHz) altimeter aboard Topex/Poseidon will provide a unique set of measurements of the ionosphere's Total Electron Content (TEC). In addition to the altimeter measurements of TEC at nadir, radio metric tracking of the satellite will provide additional TEC data along nearby lines of sight. The data will have a minimum along-track resolution of 20 km while quickly scanning a substantial latitude range between 63 deg north and south.

The altimeter measurements of TEC will be of direct use to the Topex/Poseidon mission in calibrating Tranet data, which make only a relative, not an absolute, TEC measurement. Scientifically the data are useful for investigating ionospheric TEC variations on scales ranging from 50 km to global. The shorter scales, between small instability-driven irregularities and solar-driven changes, have been little studied previously. These smaller scales are of interest because they may contain the largest amount of power in the ionospheric irregularity spectrum. At the larger scales the fluctuations may relate solar influences to other ionospheric and atmospheric variability. Of course, larger scale variations such as the equatorial anomaly or hemispherical differences could also be investigated. The homogeneity of the data would be a great asset for such work. The three to five year Topex/Poseidon mission will allow for some investigation of the changes of the ionosphere over a major part of a solar cycle.

The Topex/Poseidon altimeter will measure the ionospheric TEC with an accuracy of $\pm 3 \times 10^{16}$ electrons/m^2. This is 50% of the typical nighttime value and 5% of the daytime peak TEC. Unlike plasma analyzers, the instrument should have no internal drifts, and the data should be strictly noise limited. This will allow long baseline geographical and temporal comparisons.

The 40 to 50 Doris stations will measure the TEC derivatives along the station-to-satellite line of sight. There will be on the average 250 passes a day with a global coverage. These data are also useful for studying the Earth's ionosphere.

Section V
Topex/Poseidon and Other Programs

The Topex/Poseidon mission fits naturally into current national and international discussions of optimum strategies for measuring the oceans over the next decade. With the end of the Global Weather Experiment that investigated the possibility of forecasting weather one to two weeks in advance, meteorological interest has begun to shift toward the second objective of the Global Atmospheric Research Program—that of understanding climate and its changes. In contrast to weather, the slow variability of the climate means that the role of the ocean cannot be regarded as secondary. For example, the question of whether the ocean really carries as much of the meridional heat flux as calculated by some meteorologists (e.g., Oort and Von der Haar, 1976; Hastenrath, 1980; Trenberth, 1979) is of considerable importance in understanding global climate and its changes. Other climatologically important questions are of immediate interest to national policy. For example, we do not know the implications of the growing amount of atmospheric carbon dioxide produced by the combustion of fossil fuels because we do not know how much carbon dioxide the oceans can take up directly. Nor do we know the rate at which the ocean will warm under a warming atmosphere (see National Research Council, 1979a; Department of Energy, 1980).

These and other problems have led to national and international programs to investigate the causes of climate change and the implications for society. The international studies of the causes and predictability of climate are organized within the World Climate Research Program under the auspices of the World Meteorological Organization, the International Council of Scientific Unions, and the Intergovernmental Oceanographic Commission. Because of the importance of the oceans in the climate system, the program is built around two large-scale oceanographic experiments: the World Ocean Circulation Experiment (WOCE) and the Tropical Oceans Global Atmospheres (TOGA) experiment.

In parallel with the development of a climate research program has been the development of ocean-observing systems for practical purposes. The European Space Agency and the U.S. Navy will both launch oceanographic satellites, ERS-1 and NROSS, respectively. These will provide global observations of winds and waves of particular importance to the Ocean Topography Experiment, plus altimeter observations of sea level from ERS-1 that will supplement the Topex/Poseidon observations.

The combination of data from Topex/Poseidon, NROSS, ERS-1, and the World Climate Research Program (WCRP) will lead to a revolutionary new understanding of the ocean, its dynamics, and its interaction with the atmosphere. Displayed in Fig. 27 are currently planned timetables for the various space missions and the WCRP experiments.

A. World Ocean Circulation Experiment (WOCE)

The goal of WOCE is to collect data necessary to develop and test ocean models useful for predicting climate change, to determine the representativeness of the specific WOCE data sets for long-term behavior of the ocean, and to find methods for determining long-term changes in the oceanic circulation (Woods, 1985). The World Ocean Circulation Experiment includes several major elements in addition to altimetry (Fig. 28). One element will be a global shipboard program to measure density and chemistry. This has several goals. It would provide a measurement of the temperature and salinity of the ocean in the present epoch for comparison with past and

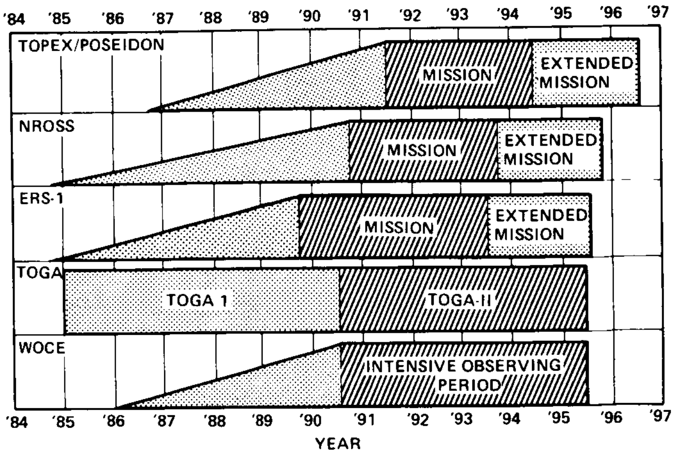

Fig. 27. Timetable for major oceanographic elements of the World Climate Research Program

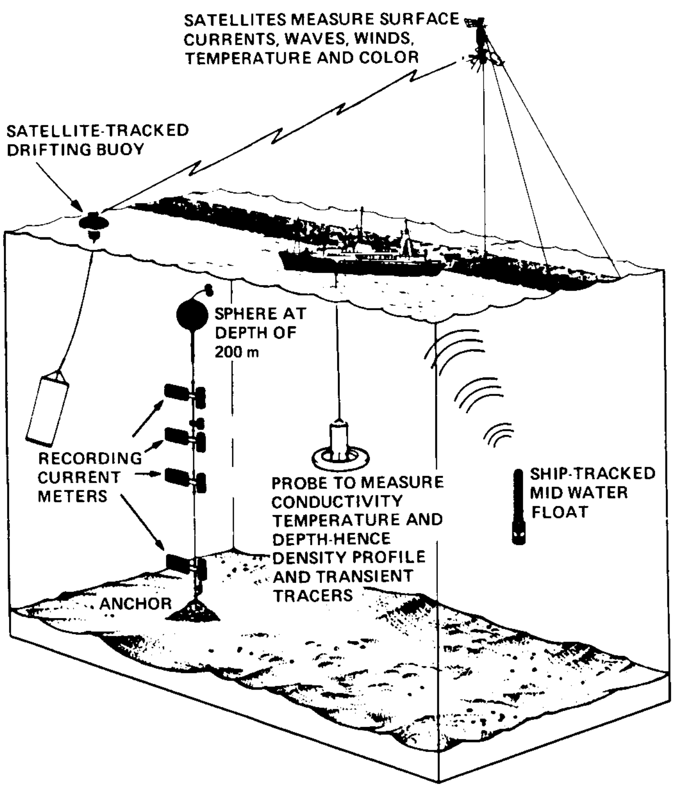

Fig. 28. Oceanographic elements of the World Ocean Circulation Experiment (after European Space Agency, 1985)

future measurements to deduce major long-term climatological changes. And it would measure the tritium and other tracer distributions for the study of the large-scale property distribution of the sea and the time-averaged velocity field at great depths.

A second major element consists of a global program to deploy and track surface and subsurface drifters. These will provide direct measurements of both geostrophic and nongeostrophic surface flows and mid-level flows that will complement the Topex/Poseidon measurements of the surface geostrophic flow.

The third major element consists of a program to model the general circulation of the ocean using a combination of eddy-resolving and thermodynamic models of circulation. Such models will be used with surface and subsurface data collected by the field programs and surface currents, winds, and heating measured by the satellite programs. These data would be assimilated into the models in ways that are analogous to the way meteorological data are assimilated into models of the atmospheric general circulation.

The various elements of the World Ocean Circulation Experiment will have special importance to the Topex/Poseidon investigations. In any given ocean basin the subsurface measurements by hydrography and drifters, when combined with the Topex/Poseidon data, will allow the first direct determination in absolute units of the geostrophic, general circulation of the ocean. In addition, because ships can only cover the world's oceans sequentially, Topex/Poseidon would provide a unique measure of the interbasin variability on the annual and interannual time scales necessary for permitting an understanding of the representativeness of any survey of an ocean at a particular time.

In addition, many purely regional experiments will be conducted because of the availability of the Topex/Poseidon measurements. These experiments will require little international coordination, but it is important that the Topex/Poseidon timetable and capabilities be widely disseminated long in advance of the actual mission because the logistics of oceanographic expeditions require considerable advanced planning.

B. Tropical Ocean and Global Atmosphere (TOGA)

The equatorial regions of the world's oceans are special. They appear to be directly coupled to the atmosphere and to have a much stronger and more obvious influence on climate than do mid-latitude oceans. They are dynamically distinct and contain such features as undercurrents and equatorially trapped waves. Furthermore, the equatorial Pacific gives rise to the dramatic El Niño phenomenon with consequences for both fisheries and climate.

The increasing information that the El Niño phenomenon is but one local manifestation of a global interaction of the ocean and atmosphere provides an example of the importance of establishing the circulation pattern over all of the tropical oceans.

The goal of TOGA is to determine the predictability of the tropical oceans and the global atmospheric system on time scales of months to years and to understand the mechanisms causing variability in the system. TOGA will include several experiments in the tropical regions of the Atlantic, Pacific, and Indian Oceans.

The Topex/Poseidon measurements of sea level and circulation in tropical oceans will directly benefit TOGA, and in turn, Topex/Poseidon will profit from the many new TOGA observations of tropical and global phenomena, including observations of the thermodynamic and wind forcing of the tropical oceans and the measurements of sea level at islands in the Pacific and Atlantic. The latter observations will be especially helpful for calibrating, to the required accuracy, the Topex/Poseidon altimeter system.

C. Navy Remote Ocean Sensing System (NROSS)

NROSS is a satellite system designed to provide measurements of near-surface wind, wave height, sea-surface temperature, and atmospheric water content over the global oceans (Freilich, 1985). It is primarily a Navy mission with close collaboration with NASA, NOAA, and the Air Force. It will have four microwave instruments: (1) a scatterometer (provided by NASA and called NSCAT; see Freilich, 1985), (2) a radar altimeter, (3) a multifrequency scanning microwave radiometer called SSM/I, and (4) a low-frequency scanning microwave radiometer that, in conjunction with the SSM/I data, will be used to measure sea-surface temperature with a resolution of 25 km. The spacecraft will operate in a sun-synchronous orbit at an altitude of 830 km and an inclination angle of 98.7 deg. The launch is currently scheduled for September 1990.

The scheduled simultaneous flight of NROSS is important for the Topex/Poseidon mission because the scatterometer onboard will provide the extremely important windfield measurements necessary for calculating the forced oceanic response. The wind measurement is vital for maximum use of the altimetric data both for the variability and mean ocean circulation.

D. ESA Remote Sensing Satellite-1 (ERS-1)

The ERS-1 project of the European Space Agency (ESA) will fly an oceanographic satellite with launch planned for 1989. Its payload consists of a radar altimeter, a radar scatterometer, a synthetic aperture radar, a laser retroreflector array (for tracking purpose), a radiometer (water vapor correction for altimeter), and a radiometric tracking system. The satellite will be flown in a sun-synchronous orbit at an altitude of 777 km with a nominal repeat period of 3 days. The repeat period may be changed after the initial 6-month validation period.

Although there has not been a rigorous error estimate for the ERS-1 altimeter, it is believed that its accuracy will be better than that of the Seasat altimeter but worse than that of Topex/Poseidon. A crossing-arc analysis of the two altimetric measurements will allow a calibration of the ERS-1 altimeter to a much improved accuracy. In essence, the cross-arc analysis allows the Topex/Poseidon accuracy to be transferred to the ERS-1 altimeter data. In addition, Topex/Poseidon will provide global measurements of tides which will feed back into the tidal models used to correct the ERS-1 data. The relatively low inclination of the Topex/Poseidon orbit means that the Topex/Poseidon ground tracks will cross the ERS-1 tracks at a high angle, making it possible to tie the ERS-1 tracks together and to combine the two data sets into one.

There are a number of ways in which Topex/Poseidon can take advantage of the ERS-1 satellite. The lower inclination Topex/Poseidon orbit means that the high-latitude oceans, principally the Norwegian Sea and the near-pole regions of the southern ocean, will not be covered. The high-inclination orbit of ERS-1 will cover these regions with near-meridional ground tracks. Except for the tidal aliasing problem which can be solved using Topex/Poseidon data, ERS-1 will provide coverage of the variability there. The combination of ERS-1 and Topex/Poseidon data will also allow ERS-1 to accurately measure the shape of continental ice sheets in Antarctica and Greenland, a primary goal of the Ice and Climate Experiment. In mid-latitudes, ERS-1 will provide primarily a denser surface coverage for determining the mean sea surface and mapping the mesoscale variability.

Finally, the data from the scatterometer onboard ERS-1, when combined with the data from the NASA Scatterometer on NROSS, will certainly provide a better sampled wind field to be used with the Topex/Poseidon altimetry for ocean circulation studies.

Glossary

AGC	Automatic Gain Control
AVISO	Analysis, Validation and Interpretation of Satellite Data
CNES	Centre National d'Etudes Spatiales
DOGE	Doris Orbitography and Geopotential Evaluation
Doris	Determination d'Orbite et Radiopositionement Integre par Satellite
ERS-1	ESA Remote Sensing Satellite-1
FGGE	First Global GARP Atmospheric Experiment
FNOC	Fleet Numerical Oceanographic Center
GDR	Geophysical Data Record
Geos-3	Geodynamic Experimental Ocean Satellite-3
GRGS	Groupe de Recherche en Geodesie Spatiale
GRM	Geopotential Research Mission
GSFC	Goddard Space Flight Center
IGDR	Interim Geophysical Data Record
JPL	Jet Propulsion Laboratory
K_u-Band	12.5–18.6 GHz
LOD	Length of Day
MEDOC	Motion of the Earth by Doppler Observing Campaign
MERIT/COTES	Monitor Earth Rotation and Intercompare the Techniques/Conventional Terrestrial Reference System
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmospheric Administration
NODS	NASA Ocean Data System
NROSS	Navy Remote Ocean Sensing System
POD	Precision Orbit Determination
Poseidon	French project for ocean and ice dynamics
SSM/I	Special Sensor Microwave/Imager
TDIF	Topex/Poseidon Data Information Facility
TDRSS	Tracking and Data Relay Satellite System
TEC	Total Electron Content
TOGA	Tropical Ocean and Global Atmosphere Experiment
Topex	U.S. Ocean Topography Experiment
VLBI	Very Long Baseline Interferometry
WCRP	World Climate Research Program
WOCE	World Ocean Circulation Experiment

PRECEDING PAGE BLANK NOT FILMED

References

Bernstein, R. L., and W. B. White, 1974. Time and length scales of baroclinic eddies in the central north Pacific Ocean. *J. Phys. Oceanogr. 4*, 613-624.

Breakwell, J., 1979. Satellite determination of short wavelength gravity variations. *J. Astronaut. Sci.* XXVII (4), 329.

Cartwright, D. E., 1977. Ocean tides. *Reports on Progress in Physics 40*, 665-708.

Cartwright, D. E., B. D. Zetler, and B. V. Hamon, 1979. *Pelagic Tidal Constants*. Paris: IUGG Publications Office, IAPSO Publication Scientifique No. 30.

Cartwright, D. E., A. C. Edden, R. Spencer, and J. M. Vassier, 1980. The tides of the northeast Atlantic Ocean. *Phil. Trans. R. Soc. London, Ser. A298*, 87-139.

Cazenave, A., B. Lago, and K. Dominh, 1982. Geoid anomalies over the Northeast Pacific Fracture Zones from satellite altimeter data. *Geophys. J. R. Astr. Soc. 69*, 15-31.

Cazenave, A., B. Lago, and K. Dominh, 1983. Thermal parameters of the oceanic lithosphere estimated from geoid height data. *J. Geophys. Res. 88*, 1105-1118.

Charney, J. G., 1955. The Gulf Stream as an inertial boundary layer. *Proc. Nat. Acad. Sci. USA 41*, 731-740.

Chelton, D. B., and P. McCabe, 1985. A review of satellite altimeter measurement of sea surface wind speed: with a proposed new algorithm. *J. Geophys. Res. 90* (C3), 4707-4720.

Cheney, R. E., and J. G. Marsh, 1981a. Seasat altimeter observations of dynamic ocean currents in the Gulf Stream region. *J. Geophys. Res. 86*, 473-483.

Cheney, R., and J. G. Marsh, 1981b. Oceanographic evaluation of geoid surfaces in the western North Atlantic. In *Oceanography from Space*, J. F. R. Gower, Ed. New York: Plenum Press, pp. 855-864.

Cheney, R. E., J. G. Marsh, and B. D. Beckley, 1983. Global mesoscale variability from collinear tracks of Seasat altimeter data. *J. Geophys. Res. 88*, 4343-4354.

Choy, L. W., D. L. Hammond, and E. A. Uliana, 1984. Electromagnetic bias of 10-GHz radar altimeter measurements of MSL. *Mar. Geod. 8*(1-4), 297-312.

CNES, 1983. *Poseidon*. Paris: Centre National d'Etudes Spatiales.

Cutting, E., G. H. Born, and J. C. Frautnick, 1978. Orbit analysis for Seasat-A. *J. Astronaut. Sci. 26*(4), 315-342.

Daniault, N., and V. Menard, 1985. Eddy kinetic energy distribution in the southern ocean from altimetry and FGGE drifting buoys. *J. Geophys. Res. 90*(C6), 11,877-11,889.

Dawson, James, 1977. Freak ocean waves are episodic. *New Scientist 72*(1033), 7-9.

Department of Energy, 1980. Carbon dioxide effects, research and assessment program. Paper presented at the Workshop on Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change, CONF-7904143, UC-11, 470 pp.

Dietrich, G., 1944. Die schwingungssysteme der half und eintagigen tiden in den ozeanen. *Veroeffentl. Inst. Meerskunde Univ. Berlin A41*, 7-68.

Douglas, B. C., C. Goad, C. Morrison, and F. Foster, 1980. A determination of the geopotential from satellite-to-satellite tracking data. *J. Geophys. Res. 85*(B10), 5471-5480.

Duing, W. O., and C. N. K. Mooers, 1977. Low-frequency variability in the Florida Current and some relation to atmospheric forcing, 1972-1974. *J. Mar. Res. 35*, 129-161.

Engelis, T., 1983 *Analysis of Sea Surface Topography Using Seasat Altimeter Data.* Columbus: Department of Geodetic Science and Surveying, The Ohio State University, Report No. 343.

Engelis, T., 1985. Global circulation from Seasat altimeter data. *Mar. Geod. 9*, 45-69.

Engelis, T., C. Tscherning, and R. Rapp, 1984. Comparisons of geoid undulation differences in central Ohio. *EOS Trans. AGU 65*(16), 180.

European Space Agency, 1985. *Looking Down, Looking Forward*. Paris: European Space Agency, Special Publication SP-1073, 53 pp.

Farless, D. L., 1985. The application of periodic orbits to TOPEX mission design. AAS/AIAA Astrodynamics Conference paper AAS 05-301; available from the Topex Project, Jet Propulsion Laboratory, Pasadena, CA, 91109.

Freilich, M. H., 1985. *Science Opportunities Using the NASA Scatterometer on the N-ROSS*. Pasadena: Jet Propulsion Laboratory, JPL Publication 84-57, 36 pp.

Fu, L.-L., 1983a. Recent progress in the application of satellite altimetry to observing the mesoscale variability and general circulation of the ocean. *Rev. Geophys. Space Phys. 21*(8), 1656-1666.

Fu., L.-L., 1983b. On the wave number spectrum of oceanic mesoscale variability observed by the Seasat altimeter. *J. Geophys. Res. 88*, 4331-4342.

Fu., L.-L., and D. B. Chelton, 1985. Observing large-scale temporal variability of ocean currents by satellite altimetry: with application to the Antarctic Circumpolar Current. *J. Geophys. Res. 90*, 4721-4739.

Ganeko, Y., 1983. A 10′ × 10′ detailed gravimetric geoid around Japan. *Mar. Geod. 7*, 291-314.

Greenwood, J. A., A. Natham, G. Newmann, W. J. Pierson, F. C. Jackson, and T. E. Pease, 1969. Radar altimetry from a spacecraft and its potential applications to geodesy. *Remote Sensing of Environment 1*, 59-70.

Harris, R. W., 1904. Physical hydrography, manual of tides (pt. IVb, cotidal lines of the world; Appendix 5). *Report of the U.S. Coast and Geodetic Survey*. Washington, D. C.: U.S. Government Printing Office, 315-400.

Hastenrath, S., 1980. Heat budget of tropical ocean and atmosphere. *J. Phys. Oceanogr. 10*(2), 159-170.

Hayne, G. S., and D. W. Hancock, 1982. Sea-state-related altitude errors in the Seasat radar altimeter. *J. Geophys. Res. 87*(C5), 3227-3231.

Hendershott, M. C., 1977. Numerical models of ocean tides. In *The Sea*, vol. 6, E. D. Goldberg, I. M. McCave, J. J. O'Brien, and J. H. Steele, eds. New York: Wiley-Interscience.

Hendershott, M., 1981. Long waves and ocean tides. In *Evolution of Physical Oceanography: Scientific Surveys of Henry Stommel*, B. A. Warren and C. Wunsch, eds. Cambridge: The MIT Press, 292-341.

Hoge, F. E., W. B. Krabill, and R. N. Swift, 1984. The reflection of airborne UV laser pulses from the ocean. *Mar. Geod. 8*(1-4), 313-344.

Huang, N. E., C. D. Leitas, and C. G. Parra, 1978. Large-scale Gulf Stream frontal study using GEOS 3 radar altimeter data. *J. Geophys. Res. 83*, 4673-4682.

Jekeli, C. and R. Rapp, 1980. *Accuracy of the Determination of Mean Anomalies and Mean Geoid Undulation for a Satellite Gravity Field Mapping Mission*. Columbus: Ohio State University, Geodetic Science Report No. 307.

Lambeck, K., 1980. *The Earth's Variable Rotation: Geophysical Causes and Consequences*. Cambridge: Cambridge University Press.

Lambeck, K., and R. Coleman, 1983. The Earth's shape and gravity field: a report of progress from 1958 to 1982. *Geophys. J. R. Astr. Soc. 74*, 25-54.

Le Provost, C., and M. Fornerino, 1985. Tidal spectroscopy of the English Channel with a numerical model. *J. Phys. Oceanogr. 15*, 1009-1031.

Lerch, F. J., S. M. Klosko, and G. B. Patel, 1982. A refined gravity model from Lageos (GEM-L2). *Geophys. Res. Lett. 9*(11), 1263-1266.

Lerch, F. J., S. M. Klosko, C. A. Wagner, and G. B. Patel, 1985. On the accuracy of recent Goddard gravity models. *J. Geophys. Res. 90*(B11), 9312-1334.

Mariner's Weather Log, 1974. Important notice – freak waves off South Africa. *Mariner's Weather Log 18*(5), 297-298.

Marsh, J. G., T. V. Martin, J. J. McCarthy, and P. S. Chovitz, 1980. Mean sea surface computation using Geos-3 altimeter data. *Mar. Geod. 3*, 359-378.

Marshall, J. C., 1985. Determining the ocean circulation and improving the geoid from satellite altimetry. *J. Phys. Oceanogr. 15*, 330-349.

Mather, R. S., R. Coleman, and B. Hirsch, 1980. Temporal variations in regional models of the Sargasso Sea from Geos-3 altimetry. *J. Phys. Oceanogr. 10*(2), 171-185.

Mazzega, P., 1983. The M2 oceanic tide recovered from Seasat altimetry in the Indian Ocean. *Nature 302*, 514–516.

Mazzega, P., 1985. M_2 model of global ocean tide derived from Seasat altimetry. *Mar. Geod. 9*, 335–363.

McKenzie, D. P., 1977. Surface deformation, gravity anomalies and convection. *Geophys. J. R. Astr. Soc. 48*, 211-238.

McWilliams, J. C., 1976. Maps from the Mid-Ocean Dynamics Experiment: part 1, geostrophic stream functions. *J. Phys. Oceanogr. 6*, 810-827.

Menard, Y., 1983. Observation of eddy field in the northwest Atlantic and Pacific by Seasat altimeter data. *J. Geophys. Res. 88*(C3), 1853-1866.

MODE Group, The, 1978. Mid-Ocean Dynamics Experiment. *Deep-Sea Res. 25*, 859-910.

Mognard, N. M. 1984. Swell in the Pacific Ocean observed by Seasat radar altimeter. *Mar. Geod. 8* (1-4), 183–210.

Munk, W., and C. Wunsch, 1979. Ocean acoustic tomography: a scheme for large-scale monitoring. *Deep-Sea Res. 26A*, 123-161.

Munk, W., and C. Wunsch, 1982. Observing the ocean in the 1990's. *Phil. Trans. R. Soc. London, Ser. A 307*, 439-464.

NASA, 1981. *Satellite Altimetric Measurements of the Ocean: Report of the TOPEX Science Working Group*. Pasadena: Jet Propulsion Laboratory, Report 400-111, 78 pp.

National Research Council, 1978. *Geodesy: Trends and Prospects*. Washington, D. C.: National Academy of Sciences, 86 pp.

National Research Council, 1979a. *Carbon Dioxide and Climate: A Scientific Assessment*. Washington, D. C. National Academy of Sciences, 22 pp.

National Research Council, 1979b. *Application of a Dedicated Gravitational Satellite Mission*. Washington, D. C.: National Academy of Sciences, Panel on Gravity and Sea Level, Committee on Geodesy, 53 pp.

National Research Council, 1983a. *Changing Climate: Report of the Carbon Dioxide Assessment Committee Board on Atmospheric Science and Climate*. Washington, D. C.: National Academy Press, 496 pp.

National Research Council, 1983b. *Toward an International Geosphere-Biosphere Program: A Study of Global Change*. Washington, D. C.: National Research Council, Commission on Physical Sciences, Mathematics and Resources, 81 pp.

Niiler, P. P., and W. S. Richardson, 1973. Seasonal variability of the Florida Current. *J. Mar. Res. 31*, 144-167.

Nowlin, W. D., and R. D. Pillsbury, and J. Bottero, 1981. Observations of kinetic energy levels in the Antarctic Circumpolar Current in the Drake Passage. *Deep-Sea Res. 28*, 1-17.

Oort, A. H., and T. H. Von der Haar, 1976. On the observed annual cycle in the ocean-atmosphere heat balance over the Northern Hemisphere. *J. Phys. Oceanogr. 6*, 781-800.

Parsons, B., and F. M. Richter, 1980. A relationship between the driving force and geoid anomaly associated with mid-ocean ridges. *Earth Planet. Sci. Lett. 51*(2), 445-450.

Pedlosky, J., 1979. *Geophysical Fluid Dynamics*. New York: Springer-Verlag, 624 pp.

Rapp, R. H., 1978. *Mean Gravity Anomalies and Sea Surface Heights from Geos-3 Altimeter Data*. Columbus: Ohio State University, Geodetic Sciences Report 268.

Rapp, R. H., 1981. *The Earth's Gravity Field Using Seasat Altimeter Data, Terrestrial Gravity Data, and Other Data*. Columbus: The Ohio State University, Department of Geodetic Science and Surveying, Report No. 322.

Reigber, C., G. Balmino, H. Muller, W. Bosch, and B. Moynot, 1985. GRIM gravity model improvement using Lageos (GRIM3-L1). *J. Geophys. Res. 90*(B11), 9285-9299.

Rhines, P. B., 1977. The dynamics of unsteady currents. In *The Sea*, vol. 5, E. D. Goldberg, I. M., McCane, J. J. O'Brien, and J. H. Steele, eds. New York: Wiley, 189-318.

Schmitz, W. J., 1978. Observations of the vertical distribution of low-frequency kinetic energy in the western North Atlantic. *J. Mar. Res. 36*, 295-310.

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

Stewart, R. H., 1985. *Methods of Satellite Oceanography*. Berkeley: University of California Press, 360 pp.

Stommel, H., P. Niiler, and D. Anati, 1978. Dynamic topography and recirculation of the North Atlantic. *J. Mar. Res. 36*, 449-469.

Sturges, W., 1974. Sea level slope along continental boundaries. *J. Geophys. Res. 79*, 825-830.

Tai, C. K., 1983. On determining the large-scale ocean circulation from satellite altimetry. *J. Geophys. Res.* 88, 9553-9565.

Tai, C. K., and C. Wunsch, 1983. Absolute measurement by satellite altimetry of dynamic topography of the Pacific Ocean. *Nature* 301, 408-410.

Tai, C. K., and C. Wunsch, 1984. An estimate of global absolute dynamic topography. *J. Phys. Oceanogr. 14*, 457-463.

Tapley, B. D., and G. W. Rosborough, 1985. Geographically correlated orbit error and its effect on satellite altimetry mission. *J. Geophys. Res. 90*, 11817-11831.

Tapley, B. D., J. B. Lunberg, and G. H. Born, 1984. The Seasat altimeter wet tropospheric range correction revisited. *Mar. Geod. 8*(1-4), 221-248.

Taylor, P. T., T. Keating, W. D. Kahn, R. A. Langel, D. E. Smith, and C. C. Schnetzler, 1983. GRM: observing the terrestrial gravity and magnetic fields in the 1990s. *EOS Trans. AGU 64* (43), 609-611.

Torge, W., G. Weber, H.-G. Wenzel, 1983. High resolution gravimetric geoid heights and gravimetric vertical deflections of Europe including marine areas. Paper presented at the IAG General Assembly, Hamburg.

Trenberth, K. E., 1979. Mean annual poleward energy transports by the oceans in the Southern Hemisphere. *Dyn. Atmos. Oceans 4*, 57-64.

Wagner, C., 1983. The accuracy of the low-degree geopotential: implications for ocean dynamics. *J. Geophys. Res. 88*(B6), 5083-5090.

Walsh, E. J., 1982. Pulse-to-pulse correlation in satellite radar altimeters. *Radio Sci. 17*, 786-800.

Walsh, E. J., D. W. Hancock, D. E. Hines, and J. E. Kenney, 1984. Electromagnetic bias of 36-GHz radar altimeter measurements of MSL. *Mar. Geod. 8*(1-4), 265-296.

Watts, A. B., 1979. On geoid heights derived from Geos-3 altimeter data along the Hawaiian-Emperor Seamount Chain. *J. Geophys. Res. 84*(B8), 3817-3826.

Woods, S. D., 1985. The World Ocean Circulation Experiment. *Nature 314* (6011), 501-511.

World Meteorological Organization, 1983. *Large-Scale Oceanographic Experiments in the World Climate Research Programme, Report of the JSC/CCCO Study Conference in Tokyo, 10-21 May 1983*. Geneva: World Meteorological Organization/International Council of Scientific Unions, WCRP Publications Series Number 1.

World Meteorological Organization, 1983. *First Implementation Plan for the World Climate Research Programme*. Geneva:. World Meteorological Organization, Technical Document No. 80.

Wunsch, C., 1972. The spectrum from two years to two minutes of temperature in the main thermocline at Bermuda. *Deep-Sea Res. 19*, 577-593.

Wunsch, C., 1981a. Low frequency variability of the sea. In *Evolution of Physical Oceanography: Scientific Surveys in Honor of Henry Stommel*, B. A. Warren and C. Wunsch, eds. Cambridge: MIT Press, 342-374.

Wunsch, C., 1981b. An interim relative sea surface for the North Atlantic Ocean. *Mar. Geod. 5*, 103-119.

Wunsch, C., 1984. On interferences concerning the large scale ocean circulation from remote and integrating measurements. In *Global Observations and Understanding of the General Circulation of the Oceans*. New York: National Academy Press.

Wunsch, C., and E. M. Gaposhkin, 1980. On using satellite altimetry to determine the general circulation of the ocean with application to geoid improvements. *Rev. Geophys. Space Phys. 18*, 725-745.

Wunsch, C., and A. E. Gill, 1976. Observations of the equatorially trapped waves in Pacific sea-level variation. *Deep-Sea Res. 23*, 371-390.

Wunsch, C., and V. Zlotnicki, 1984. The accuracy of altimetric surfaces. *Geophys. J. R. Astr. Soc. 78*, 795-808.

Wyrtki, K., 1975. Fluctuations of the dynamic topography in the Pacific Ocean. *J. Phys. Oceanogr. 5*, 450-459.

Wyrtki, K., 1979. Sea level variation: monitoring the breath of the Pacific. *EOS Trans. AGU 60*, 25-27.

Wyrtki, K., L. Magaard, and J. Hager, 1976. Eddy energy in the oceans. *J. Geophys. Res. 81*, 2641-2646.

Zetler, B. D., 1971. Radiational ocean tides along the coasts of the United States. *J. Phys. Oceanogr. 1*, 34-38.

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. JPL Pub. 86-18	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Science Opportunities From the Topex/Poseidon Mission		5. Report Date July 15, 1986 6. Performing Organization Code
7. Author(s) R. Stewart, L.-L. Fu, and M. Lefebvre		8. Performing Organization Report No. JPL Pub. 86-18
9. Performing Organization Name and Address JET PROPULSION LABORATORY California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109		10. Work Unit No. 11. Contract or Grant No. NAS7-918 13. Type of Report and Period Covered JPL Publication
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Washington, D.C. 20546		14. Sponsoring Agency Code RE 4 BP-161-01-01-40-00
15. Supplementary Notes 28 figures, 7 tables, glossary, and references		

16. Abstract The U.S. National Aeronautics and Space Administration (NASA) and the French Centre National d'Etudes Spatiales (CNES) propose to conduct a Topex/Poseidon Mission for studying the global ocean circulation from space. The mission will use the techniques of satellite altimetry to make precise and accurate measurements of sea level for several years. The measurements will then be used by Principal Investigators (selected by NASA and CNES) and by the wider oceanographic community working closely with large international programs for observing the Earth, on studies leading to an improved understanding of global ocean dynamics and the interaction of the ocean with other processes influencing life on Earth.

The major elements of the mission include a satellite carrying an altimetric system for measuring the height of the satellite above the sea surface; a precision orbit determination system for referring the altimetric measurements to geodetic coordinates; a data analysis and distribution system for processing the satellite data, verifying their accuracy, and making them available to the scientific community; and a Principal Investigator program for scientific studies based on the satellite observations.

This document describes the satellite, its sensors, its orbit, the data analysis system, and plans for verifying and distributing the data. It then discusses the expected accuracy of the satellite's measurements and their usefulness to oceanographic, geophysical, and other scientific studies. Finally, it outlines the relationship of the Topex/Poseidon mission to other large programs, including the World Climate Research Program, the U.S. Navy's Remote Ocean Sensing System satellite program and the European Space Agency's ERS-1 satellite program.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Topex/Poseidon Project Physical Oceanography Geodesy Spacecraft Instrumentation	Unclassified -- Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	x + 58	