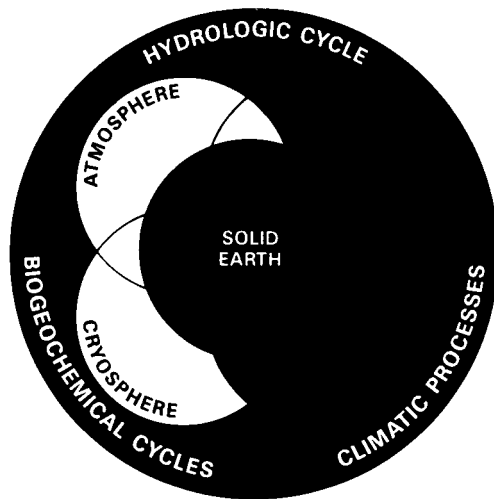


Altimetric System

EARTH OBSERVING SYSTEM
Volume III



PANEL REPORT

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EARTH OBSERVING SYSTEM REPORTS

- Volume I Science and Mission Requirements Working Group Report
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Laser Atmospheric Wind Sounder
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Panel Report

**ALTIMETRY AND PRECISION ORBIT DETERMINATION
PANEL FOR THE EARTH OBSERVING SYSTEM**

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PREFACE

Over 200 years ago, Benjamin Franklin advised his colonial compatriots that "nothing is certain but death and taxes." Sage as this judgment may be for mankind, it is a bit restrictive in an enlightened society, for there is at least one greater certainty, and that is change. Even the most casual observer notes natural changes taking place in his environment every day. Volcanoes create entirely new islands where yesterday there were none; crops are failing under the scourge or drought; fish prices have soared in the local markets.

People have always been deeply impressed, and sometimes even rudely inconvenienced, by the more spectacular (and perhaps catastrophic) events of nature. More subtle, slower changes that may well have a more profound effect on mankind have gone almost unnoticed and usually go unheralded by modern news media. Yet these changes lie at the heart of Eos, and their effects are frequently evidenced as variations in the Earth's topographic features.

Satellite altimetry combined with the modern practices of precision orbit determination provide the scientific community with an accurate and precise means of adjudging surface topographic changes. Thus, it will be through these measurements (among others) that we hope to gain a more thorough knowledge of our own environment and the significance of the changes it undergoes.

Robert R. P. Chase
Woods Hole, Massachusetts
July 1986

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EXECUTIVE SUMMARY

The purpose of this report is to provide the National Aeronautics and Space Administration (NASA) with a rationale and recommendations for planning, implementing, and operating an altimetric system aboard Eos spacecraft. In keeping with the recommendations of the Eos Science and Mission Requirements Working Group, this report defines a complete altimetric system that is capable of perpetuating the data set to be derived from TOPEX/Poseidon, enabling key scientific questions (both discipline-specific as well as multidisciplinary) to be addressed. Since the scientific utility and technical maturity of spaceborne radar altimeters have been well documented and, further, since the details of an Eos laser altimeter have been covered by the LASA Panel in their report (Curran *et al.*, 1986), we limit our discussion to highlighting those Eos-specific considerations that materially impact upon radar altimetric measurements.

The Earth Observing System Science and Mission Requirements Working Group recognized that a new class of research problems has been emerging that requires the use of a multidisciplinary approach in scientific investigations. In particular, they found that the key to successful progress in Earth science research lies in addressing those specific questions that relate to the Earth as an integrated system of processes. Treating the Earth as an integrated system of associated and interrelated or dependent processes and examining time-dependent, system-level changes, touches upon the role that altimeter systems should play during the coming decade, since the effects of these changes are frequently evidenced as variations in the Earth's topographic features. Satellite altimetry combined with the modern practices of precision orbit determination provide the scientific community with an accurate and precise means of adjudging surface topographic changes. Thus, it will be through these measurements (among others) that we hope to gain a more thorough knowledge of our own environment and the significance of the changes it undergoes.

There are many well-documented uses for precise altimetric measurements; they extend from basic research in the Earth sciences to applied problems that impact our daily lives. These problems include those directly related to significantly improving our understanding of the oceans as a whole (including ice covered regions), the physical climate system, solid Earth land masses, offshore energy production, commerce, coastal zone problems, communications, and national defense. Based upon our experience with previous satellite-borne altimeters, we believe that the accuracies and precisions needed to address these problems can be achieved from Eos platforms, thus perpetuating the high-quality data set expected from TOPEX/Poseidon and providing new data for basic

research in the Earth sciences and for operational tasks.

From a research perspective then, the goals or objectives that an Eos altimeter system should address are both discipline-specific as well as multidisciplinary. This in turn implies that the accuracy, precision, and sampling schema (i.e., geographic grid scale and coverage, and temporal resolution) associated with these measurements will be different depending upon the specific scientific question being addressed. Similarly, since the operational objectives are different, they too will yield an alternate set of measurement characteristics. The final set of design measurement requirements derived from this admixture of objectives reflects a compromise between the various sets of requirements imposed upon the overall instrument and spacecraft system.

FINDINGS AND RECOMMENDATIONS

To meet the requirements of the research and operational communities, careful consideration must be given to the concept of an altimetric instrument system. As we envision an Eos altimetric system, it would consist of TOPEX-class radar altimeters deployed on each of the three Eos platforms. Additionally, these instruments would be supported by Global Positioning System (GPS) receivers, a microwave radiometer, laser retroranger or retroreflectors, an attitude control subsystem (for the laser retroranger), onboard data subsystem, *in situ* observations of various geophysical variables, a complete ground-based data and information system, and Eos Altimetry Instrument and Precision Orbit Determination Teams.

There are significant scientific and technologic synergies that exist between the radar altimeter and other planned Eos instruments (i.e., Advanced Mechanically-Scanned Radiometer, Geodynamics Laser Ranging System, Scatterometer, Advanced Data Collection and Location System) as well as the scientific advantages of a three-radar system. Thus, while weight, power, volume, and fiscal considerations might otherwise preclude the joint deployment of all four instruments on each platform, the addition of a single TOPEX-class altimeter to each Eos platform provides a ready means of ensuring the requisite scientific synergy while yielding only very minimal impact on the Program as a whole.

TOPEX-Class Altimeter

We recommend the use of TOPEX-class radar altimeters aboard Eos platforms since they are a fourth-generation instrument that is well developed both scientifically and technologically. Further, by

using this instrument, Eos will be at an advantage relative to its prime goal of perpetuating planned, research data bases, in this case the accurate and precise measurements from the Ocean Topography Experiment. We also note that since the TOPEX/Poseidon spacecraft will likely be launched in 1991, reproduction of its basic radar altimeter and supporting subsystems will presumably have the smallest fiscal impact on the overall Eos Program, even if minor changes are made.

Multibeam Research and Development

We believe that given the lifecycle of Eos and the recommendation of the Eos Science Steering Committee to capitalize on technologic advances, the Eos Program should foster the development of multibeam radar altimetry as a prospective future replacement for the TOPEX-class Eos instruments.

We recognize that there are at least three technologic approaches that could be developed, and recommend that a study be undertaken to assess which methodology holds the greatest promise technologically, scientifically, and fiscally. Furthermore, based upon the results of this study, we recommend that a prototype instrument be developed and tested.

In addition, other key technological problems will need study before multibeam altimeters could be reliably implemented as a component of the Eos Altimetric System. The multiple beams will necessitate the use of multiple range trackers, which must be highly adaptive to function properly over relatively rough terrain. Consequently, we recommend that a research and development effort be undertaken to address this issue.

Global Positioning System

We recommend that GPS receivers be deployed aboard each Eos platform to provide sufficient information to allow precision orbit determination to be undertaken for each platform. TOPEX-class GPS receivers should have the capability of providing 10-meter onboard orbital accuracies, and post-processing should yield subdecimeter accuracies for the radial orbit component. Since this would be consistent with Eos altimetry goals, we recommend the inclusion of these receivers.

Microwave Radiometer

We recommend that Eos radar altimeters be deployed with either the Advanced Mechanically Scanning Radiometer (AMSR) or a separate, stand-alone microwave radiometer subsystem. The purpose of the microwave radiometer is to provide emission information for both rainfall measurements and for water vapor path length corrections for the radar.

AMSR can serve these functions when deployed with the radar altimeter; otherwise, a small three-channel radiometer with bands centered around 37, 21, and 18 GHz should be employed.

Laser Retro-ranger/Retroreflector

We recommend that the Geodynamics Laser Ranging System (GLRS) be jointly deployed with one of the Eos radar altimeters. The purposes of a joint deployment are both scientific and technical (in terms of platform precision orbit determination). Alternatively, we recommend that the Eos radar altimeters be deployed with separate, stand-alone space-based laser retroreflectors. Retroreflectors, however, will only address pertinent precision orbit determination and altimetric calibration issues; and they carry the concomitant problem of maintenance and upkeep of the existing ground-based laser tracking network.

We recommend that consideration be given to design modifications for the GLRS instrument. These modifications include an increase in the aperture of the receiving telescope and an increase in transmitted power, providing a means to receive a reasonable number of photoelectrons per return pulse. Beyond these modifications, we recommend careful study of the laser flashtube lifetime issue. Given the current state of technical development, it remains unclear from a cost/benefit standpoint if the added scientific and operational utility will balance the costs involved with developing a laser system with suitable design life.

Attitude Control Subsystem

Spacecraft attitude and rate of attitude change must be known at observational epochs if GLRS range measurements are to be made with an accuracy of 1 centimeter. We therefore recommend that a separate attitude control subsystem be included with the altimetric payload if the GLRS is deployed as a component of the system. An active attitude control system is preferable since it would minimize systematic errors; we recommend that this subsystem be designed with a minimum attitude maintenance capability of 1 arcsecond relative to the local vertical.

Requisite *In Situ* Observations

We note that there is a host of *in situ* observations that would be of significant scientific value to a researcher actively engaged in Eos-sponsored studies. Because of their scientific significance, we recommend that provisions be made to support their acquisition for Eos-sponsored researchers. Autonomous acquisition can best be accomplished by deploying the Advanced Data Collection and Location System (ADCLS).

Additionally, the Eos radar altimeter data processing task will require a set of *in situ* observations

to support both the verification program that we recommend and the reduction of the altimetric data to geophysical data records (GDR). These observations include atmospheric pressure and temperature, sea state, wind velocity, and water vapor pressure. Some of these data are available from sources such as National Oceanic and Atmospheric Administration (NOAA) and Fleet Numerical Oceanography Central (FNOCC), while others must be obtained specifically within the geographic region used for verification purposes. We recommend that the Eos Program provide ready access to the requisite data, preferably electronically.

Eos Data and Information System

We concur with and fully support the recommendations of the Eos Data Panel concerning the need for a complete data and information system. We recommend that those specific components dedicated to the acquisition and production of altimetric data, including both hardware and software, should be installed and fully functional at least 6 months prior to launching the first platform. We further recommend that this portion of the system should be thoroughly tested during this 6-month period and that any noted deficiencies be remedied before launch.

Since the Eos Data Panel recommended that data be processed beyond Level 1 only on request, we hereby request that all altimeter data be routinely processed to Level 2. We further recommend that a select subset of both AMSR and scatterometer data be routinely reduced to Level 2 over the specific geographic region that will be used for verification purposes.

Altimetry Teams

We strongly recommend that the scientific community be involved in the development and subsequent operation of Eos altimeters from the outset and throughout all subsequent activities, since the data will be acquired, transmitted, processed, and delivered for scientific purposes. We recommend that researchers also be given an oversight and review responsibility, and suggest that this might best be accomplished through the establishment of an Altimetry Instrument Team.

Further, because of the critical dependence of scientifically useful altimetric data on precision orbit determination, we also recommend that a closely allied Precision Orbit Determination Team be established to work with both the Altimetry Instrument Team and Project personnel.

Orbit Selection

We recommend that careful consideration be given to sun-synchronous "frozen" orbits as a viable

alternative to purely circular orbits. If some other instrument cannot tolerate a modestly eccentric orbit, we recommend that the current scenario that utilizes three platforms at 824 kilometers in circular, sun-synchronous orbits be adopted as the nominal baseline.

Platform Structural Rigidity

We are concerned with the novel, new structures that are being proposed for the Space Station polar platforms, hence the Eos spacecraft. Significant levels of flexure (yielding virtually undetectable altimetric data contamination) in these modular structures seem inevitable. Consequently, we recommend that Project personnel become closely involved in Space Station Project activities, ensuring that the best interests of the Eos altimetric system are considered.

Antenna Location

We recommend that the radar altimeter antenna be positioned with the minimum possible moment arm from the platforms' center of mass. By positioning the antenna as closely as possible to the center of mass, the effects of platform flexure will be minimized. This will, in turn, minimize any time-dependent errors (which are difficult to model) resulting from these factors.

Center of Mass Knowledge

Assuming that GLRS is jointly deployed on at least one platform with a radar altimeter, its location relative to the center of mass of the spacecraft must be known to better than 1 centimeter if the resultant data are to be used for precision orbit determination. We therefore recommend careful examination of initial instrument placements and subsequent replacement strategies.

CONCLUSION

Based upon the wealth of documentation supporting the utility of high-precision altimetric measurements and our analysis of Eos goals and platform capabilities, we believe that Eos can achieve its prime goal of perpetuating research data sets for studies of Earth System Science. *We therefore recommend that serious consideration be given to the inclusion of a high-precision Altimetric System, based upon a TOPEX-class radar instrument, on all Eos platforms.* Further, we recommend deployments of AMSR, scatterometer, and GLRS, so that at least one of these instruments can be operated synergistically with an Eos radar altimeter on each of the platforms, thereby maximizing the scientific utility of Eos spacecraft. We also recommend that an appropriate data system be designed, implemented, and operational at least 6 months prior to launch. We further recommend

that the development of multibeam radar altimeter technology be continued since the promise of this emerging technology for new and otherwise unobtainable measurements is high. Finally, and perhaps most important, we recommend that the scientific community be involved in the design and implemen-

tation of the Eos Altimeter System; this involvement might best be accomplished through the establishment of active Altimetry Instrument and Precision Orbit Determination Teams with representatives from appropriate scientific and engineering disciplines and from the operational sector.

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ACRONYMS

ADCLS	Advanced Data Collection and Location System
ALT	Altimeter
AMSR	Advanced Mechanically Scanning Radiometer
C/A Code	Clear Acquisition Code
CW	Continuous Wave
Eos	Earth Observing System
ERS	Earth Resources Satellite
ESA	European Space Agency
FNOC	Fleet Numerical Oceanography Central
GDR	Geophysical Data Records
GEOS-3	Geodetic Earth Orbiting Satellite-3
GLRS	Geodynamic Laser Ranging System
GPS	Global Positioning System
GRM	Geophysical Research Mission
HIRIS	High-Resolution Imaging Spectrometer
JERS	Japanese Earth Remote Sensing Satellite
LASA	Lidar Atmospheric Sounder and Altimeter
MODIS	Moderate-Resolution Imaging Spectrometer
OD	Orbit Determination
P-Code	Precise Code
POD	Precision Orbit Determination
PPS	Pulses Per Second
PRF	Pulse Repetition Frequency
PRN	Pseudorandom Noise
rss	Root-Sum-Square
SAR	Synthetic Aperture Radar
SCATT	Scatterometer
SDR	Sensor Data Record
SMMR	Scanning Multifrequency Microwave Radiometer
SWH	Significant Wave Height
TDRS	Tracking Data Relay Satellite
TDRSS	TDRS System
TECU	Total Electron Content Unit
TREM	Tropical Rainfall Explorer Mission
TWT	Travelling Wave Tube
WOCE	World Ocean Circulation Experiment

I. INTRODUCTION

The scientific basis of the Earth Observing System (Eos) focuses on three fundamental cycles: those of energy, water, and biogeochemicals. The processes affecting changes in these cycles cover a spectrum of time and space scales, although their effects are frequently measurable in terms of a single variable, topographic elevation. A key ingredient, therefore, in assessing changes in our global, natural environment is knowledge of the Earth's topographic relief or surface elevation.

In principle, there are numerous ways of measuring surface elevation. Global measurements of land and ice sheet surfaces can best be performed with space-based lasers, although radar altimeters are useful as well. For the vast majority of the Earth's surface (the 78 percent covered by the oceans), we have only one proven method: space-based radar altimetry. Consequently, in this report we examine the scientific requirements for altimetric measurements in general but concentrate our technical discussion on radar altimeters and the synergies that exist between these radars and other instruments and instrument systems. A more thorough treatment of laser altimetry can be found in a companion report entitled "LASA: Lidar Atmospheric Sounder and Altimeter" (Curran *et al.*, 1986).

The microwave radar altimeter is one of the simplest of active remote sensing instruments, although it was conceived and developed for spacecraft utilization relatively recently (Barrick and Swift, 1980). Initially, it was suggested as a tool for measuring the instantaneous mean sea level for geodetic, topographic, and large-scale ocean circulation studies (Greenwood *et al.*, 1969). Some investigators recognized its potential as a sea-state sensor (Godbey, 1964) since the heights of the waves intercepted by the altimeter pulse are clearly evidenced in the echo. Surface waves (and their progenitor, the wind) therefore are measurable with a radar altimeter and play an important role in the interpretation of the signal.

The analysis and physical understanding of the interaction between radar altimeter signals and the sea is currently subject to few uncertainties; first-order algorithm development has been completed. In simplest terms, the short pulse of a satellite altimeter is "stretched" by the waves when scattering occurs across crests and troughs as the spherical pulse (wave front) progresses downward. Miller and Hayne (1972) as well as Barrick (1972a) showed that this stretching is related to the probability density function of the surface height. Barrick (1972a; 1972b) derived quantitative expressions for the echo using specular-point theory, which shows that the many small specular reflectors superposed on the longer, higher-amplitude swell produce the altimeter echo. Yaplee *et al.* (1971) produced the first tower-based altimetric data that confirmed the validity of these theories.

Short-pulse altimeters can operate in either of two modes: pulse limited and beam limited. In the pulse-limited extreme, the echo return rises as the pulse at the nadir position initially produces scatter from the wave crests, then mid-points, and finally the wave troughs. Then, however, the echo signal remains at this maximum (the plateau region) because the spherical radar pulse continues to intercept constant annular mean surface area as it spreads outward from the nadir point. The plateau eventually falls off either because of the finite antenna beamwidth or because there are fewer specular points having the required slopes farther from nadir. In this mode, sea-state information is contained on the echo leading edge as a double convolution of the height probability density function. The leading-edge time derivative is, therefore, a single convolution of this height density with the pulse shape.

By using models, such as a Gaussian sea height probability function, closed-form expressions have been derived for the leading edge and its derivative. Nearly all of the algorithms currently in use today employ maximum-likelihood (or least-squares) techniques to fit these models to the leading edge (or its derivative), thereby yielding wave height and the mean surface position.

In the beam-limited case, the pulse can be considered as a very narrow cone (representing the antenna beamwidth) as it progresses downward across the waves. The echo shape (as a function of time) is directly proportional to the height probability density function of the ocean waves, and the mean sea surface is located at the echo peak position. This operational mode can be realized from aircraft or towers, but has not been tested from a satellite.

Three generations of satellite-based, pulse-limited microwave altimeters have been deployed, and by the time the Eos platforms are deployed, a fourth-generation radar altimeter will have been placed into orbit. The first of these altimeters was S193, deployed aboard Skylab in 1973. It supported five proof-of-concept experiments to provide data needed for the design of future spacecraft radar altimeters. The five experiment modes are described in detail by Miller and Hammond (1972). One of the modes, the Radar Cross Section and Altimeter Experiment, was designed to investigate the accuracy, precision, and overall practicability of satellite radar altimeters to: (1) determine the mean sea level, (2) dynamically monitor the mean surface slopes, and (3) measure small-scale departures of the ocean surface from overall mean sea level in regions of special geodetic interest. The precision of range measurements from this first space-based radar altimeter was quite crude (McGoogan, 1975) compared to contemporary instrumentation and was further degraded by perturbations in the vertical component of the spacecraft's

orbit resulting from astronaut activities. Nevertheless, the data served valuable scientific purposes (Peirson *et al.*, 1978) and further tantalized the research community for additional data.

As a result of Skylab's success with S193, NASA deployed its first dedicated radar altimeter satellite, Geodetic Earth Orbiting Satellite-3 (GEOS-3), in 1975. Launched into an 843 km, 114.98° retrograde orbit, it had both intense and global sampling modes. The intensive operating mode of this altimeter (operating at 13.9 GHz) provided 20 cm precision with overall height accuracy of order 60 cm. Principle error sources for GEOS-3 included orbital uncertainty, attitude error, and unmeasured geophysical effects (e.g., wet and dry tropospheric errors, ionospheric electron content). The GEOS-3 radar altimeter provided a wealth of data over its nearly 3½-year lifetime. With an accuracy and precision far in excess of that achievable with S193, the GEOS-3 data are still in wide scientific use even today.

The scientific community saw a third radar altimeter deployed by NASA aboard Seasat in 1978. Optimized for oceanographic purposes, Seasat was deployed into a nominal 800 km, 108° retrograde orbit. Subsequent to its premature demise, the resultant altimeter data have been used for a wide variety of scientific investigations in physical oceanography, geophysics, cryospheric sciences, and geology (Bernstein *et al.*, 1979). Seasat's radar altimeter has proven the value and scientific utility of spaceborne topography measurements and has provided the research community with a new tool whose capabilities cannot be matched by conventional measurement techniques. Post-launch engineering evaluations indicated 10 cm range precision (Tapley *et al.*, 1982a) for this altimeter. The residual error budget for Seasat is dominated by the gravity-related orbital error, which was determined to be 140 cm. Since all other errors were significantly less, 1.5 m accuracy is an order of magnitude estimate of accuracy for this altimeter (Tapley *et al.*, 1982a).

Based upon this heritage of increasingly accurate and precise characterization of the Earth's surface topography through space-based radar altimetry, and the resulting scientific progress evidenced with each successive deployment of a new instrument, the Department of Defense launched Geosat, a dedicated radar altimeter satellite for geodetics, in 1985. Similarly, NASA together with the Centre National d'Etude Spatiales have begun work on an ocean topography experiment (known as TOPEX/Poseidon) that will utilize a dedicated Earth orbiting satellite for radar altimeter measurements of the sea surface. TOPEX/Poseidon promises to provide the highest accuracy and precision yet obtained from satellite radar altimeters, following suit as a fourth-generation scientific instrument. As currently defined, this altimeter system includes (1) a two-frequency altimeter using observations made in two channels (13.6 and 5.3 GHz) to make ionospheric corrections; (2) a three-

frequency (37, 21, and 18 GHz) nadir-looking microwave radiometer for making tropospheric water vapor corrections; and (3) Tranet beacon, laser retroreflector, and French Doris receiver for orbit tracking. The system will be flown at an orbital altitude of 1,334 km (optimal for precision orbit determination) with an inclination angle of 63.1° (optimal for ocean tide determination).

As currently defined, the TOPEX altimeter should achieve a precision of order 2 cm. The 2 kW gridded Travelling Wave Tube (TWT) used on earlier altimeters will be replaced with a longer-life, low power (20 W) TWT to satisfy the requirements for a 1.5- to 3-year lifetime for the mission. The decrease in power is to be offset by an increase in the uncompressed pulse length to 102.4 μs. The compression ratio of 32,768:1 yields a compressed pulse width of 3.125 ns, the same as Seasat. The Pulse Repetition Frequency (PRF) will be increased to 4,000 for the 13.6 GHz channel. This higher PRF and the addition of a second channel at 5.3 GHz for ionospheric corrections are major changes in spacecraft altimetry. Basically, the instrument is similar to the Seasat design with these improvements being made to provide significantly better precision tracking characteristics. Additionally, the TOPEX unit will have a bank of 128 waveform samplers that can be selected in various combinations to adapt to changing surface roughness. A 80186 microprocessor has been selected for required onboard processing and to control the altimeter's operation.

As a scientific instrument system, TOPEX/Poseidon has been designed for optimal performance by minimizing drag and through careful attention to orbit selection. Acquiring data of similar veracity with Eos altimetry will not be a trivial task. Indeed, to do so will require defining an overall instrument system for making topographic measurements that is dependent upon not just the radar altimeter per se but also upon ancillary measurements from other instruments and instrument systems and thorough, carefully conceived and executed calibration and verification studies.

In keeping with the Eos Science and Mission Requirements Working Group recommendations, this report defines an Eos altimetric system capable of perpetuating the data set to be derived from TOPEX/Poseidon, enabling key scientific questions (both discipline-specific as well as multidisciplinary) to be addressed. Since the scientific utility and technical maturity of spaceborne radar altimeters have been well documented and since the details of an Eos laser altimeter have been covered by the LASA Panel in their report, we limit our discussion to highlighting those Eos-specific considerations that materially impact upon altimetric measurements.

On this basis, this report outlines the broad goals and objectives of the Earth Observing System program with emphasis on those most closely affecting

measurement requirements to be imposed on a new altimetric system. Subsequently, specific discipline-oriented scientific objectives are given and these are translated into measurement requirements for a radar altimeter aboard an Eos spacecraft. We then review radar altimeters and examine prospects for advanced systems capable of perpetuating the high quality data expected from TOPEX/Poseidon. Data systems are

then considered with an eye toward maximizing the utility of the altimeter measurements. Finally, synergistic uses of other Eos instruments are factored into an overall system consideration for altimetry onboard an Eos platform. This report concludes with a set of recommendations for radar altimeters and altimetric systems directed toward the Eos program, specifically.

II. MISSION OBJECTIVES

The broad objectives or goals that an altimetric system aboard an Eos platform should address can conveniently be divided into two categories. These are scientific objectives and operational objectives. While these objectives are not entirely different, the resulting "requirements" derived from them and promulgated by research and operational community interests, in fact, are frequently different. In this section, we therefore outline overall mission objectives from both the research and operational sectors' viewpoints.

Eos SCIENTIFIC OBJECTIVES

The Earth Observing System Science and Mission Requirements Working Group (Butler *et al.*, 1984) recognized that a new class of research problems has been emerging that requires the use of a multidisciplinary approach in scientific investigations. In particular, they found that the key to successful progress in Earth science research lies in addressing those specific questions that relate to the Earth as an integrated system of processes. From this premise, the Science and Mission Requirements Working Group has established a set of general goals and objectives that touch upon the role that altimeter systems should play during the coming decade.

Treating the Earth as an integrated system of associated and interrelated or dependent processes and examining time-dependent, system-level changes suggest that many important processes of the Earth system have time scales ranging from days to decades. Thus, continuous measurements of a suite of variables over significantly long time periods are required to accurately characterize this spectrum of time-varying processes. Consequently, to provide adequate long-term data records, one must start with available data sets and perpetuate their acquisition, improving upon the accuracy and precision of the measurements as technology and other resources permit.

Based upon this stance, the Eos Science and Mission Requirements Working Group has recommended that several discipline-oriented research missions be carried out, their data sets being extended in time through the deployment of additional instrumentation aboard Eos platform(s). In like fashion, they recommended that measurements provided via operational spacecraft be perpetuated. This recommendation includes, among others, deployment of the Ocean Topography Experiment (TOPEX/Poseidon) spacecraft with its associated advanced radar altimeter.

The Ocean Topography Experiment will provide a data set that will allow the time-dependent and time-averaged ocean currents to be characterized to a relatively high accuracy, determining for the first time the general circulation pattern of the global oceans. TOPEX/Poseidon will utilize a radar altimeter aboard a free-flying platform deployed at a nominal altitude of 1,334 km in a 63.4° prograde orbit. This experiment has been designed specifically to measure the surface topography from which large-scale geostrophic currents can be calculated. Thus, one scientific objective of Eos is to continue acquisition of sea surface topographic measurements to similar or higher accuracy and precision than expected from TOPEX/Poseidon. In doing so, many of the long-term changes and variability associated with seasonal to secular (i.e., climate) time scales can be better characterized.

Beyond the specifics of radar altimetry for circulation studies and climatology, the Eos Science and Mission Requirements Working Group conceptually placed the radar altimeter into a "package" consisting of active microwave instruments. This grouping included radar scatterometers and synthetic aperture radars (SAR) and was included specifically to address major discipline-specific problems in physical oceanography and cryospheric sciences. By considering the synergistic uses of multiple instruments (either intra- or inter-package), the Science and Mission Requirements Working Group concluded that highly significant problems in other disciplines, as well as in multidisciplinary fields, might benefit as well.

As an example, to quantify air-sea boundary exchange processes, measurements are needed of sea surface temperature, sea state, sea surface wind, humidity, atmospheric temperature profile, etc. The Moderate-Resolution Imaging Spectrometer (MODIS) and the AMSR will provide a means for acquiring accurate sea surface temperature. The radar altimeter (ALT) and scatterometer (SCATT) provide measurements of sea state and surface wind speed and direction. The Lidar Atmospheric Sounder and Altimeter (and to a degree the AMSR) will measure atmospheric water vapor. Atmospheric temperature will be obtained from operational sounders and perhaps from the Lidar Atmospheric Sounder and Altimeter (LASA). Thus, a comprehensive data set for studies of air-sea exchange processes can be formed from measurements made by instruments that serve a variety of other purposes, the altimeter fulfilling a key function.

OPERATIONAL OBJECTIVES

Civil operational objectives for altimetry can be inferred from the overall agency responsibilities of NOAA, which is chartered to provide public benefits through the analysis, forecast, and study of Earth environmental conditions. Among others, its objectives include providing ocean and coastal zone management services and information products in support of national needs, supporting the development and utilization of the oceans and the management of marine and coastal resources, promoting improvements in marine and coastal commerce and safety of marine and coastal activities, facilitating the development of ocean mineral resources and energy, and conducting national assessments of marine resource utilization (Hussey, 1985). Agencies such as NOAA are thus tasked with routinely providing a full suite of services to the public, services that in large part are directly based upon results coming from the research community. As a consequence, the objectives of both the operational and research sectors are distinct but very much interrelated, although the translation of these objectives into instrument system requirements are frequently quite different.

SUMMARY

From a research perspective then, the goals or objectives that an Eos altimeter system should address are both discipline-specific as well as multidisciplinary. This in turn implies that the accuracy, precision, and sampling schema (i.e., geographic grid scale and coverage, and temporal resolution) associated with these measurements will be different depending upon the specific scientific question being addressed. Similarly, since the operational objectives are different, they too will yield an alternate set of measurement characteristics. The final set of design measurement requirements derived from this admixture of objectives will consequently reflect a compromise between the various sets of requirements imposed upon the overall instrument and spacecraft system.

In the next section, we explore specific research objectives for altimetric systems in oceanography, geodynamics, glaciology and cryospheric sciences, geology, and physical climatology, and the translation of these objectives into requirements to be levied upon an Eos altimetric system. In similar fashion we present altimeter requirements derived from various published documents compiled by NOAA.

III. SCIENTIFIC OBJECTIVES AND MEASUREMENT REQUIREMENTS

In this section we look more closely at specific scientific objectives and translate these objectives into overall measurement requirements for an altimetric system deployed aboard an Eos platform. We also include specific altimetric requirements published by NOAA as representative of the requirements imposed by the civil operational community.

OCEANOGRAPHY

The main scientific goal of Eos is to understand, quantify, and predict the three main cycles of the Earth system: the energy cycle, the water cycle, and the life cycle. The ocean is a key element in all of the three cycles. Through its large heat capacity, the ocean stores a major portion of the heat content of the Earth system and modulates the temperature extremes on Earth, helping to create a habitable environment for life. The ocean is also the reservoir for the Earth's entire water resource. Through circulation, evaporation, and precipitation, the ocean regulates the water supplies for the global Earth. In addition to its influence on the energy and water cycles that are essential to life on Earth, the ocean itself is the living environment for marine animals and plants that constitute an important food supply for the human population. Further, it is a repository of many biogeochemicals that support and sustain life as we know it here on Earth. Thus, observing the ocean so that we can understand, quantify, and predict the ocean's role in the ever-changing Earth system is a major objective of the Earth Observing System.

The ocean is a turbulent, global fluid medium with a rich spectrum of motions on scales ranging from millimeters (small-scale turbulence) to 10,000 km (the width of the largest ocean basin). Owing to the nature of non-linear dynamics that govern processes in the ocean, the motions at different spatial scales are linked together both dynamically and kinematically. Since no single instrument can cover this vast range of spatial scales, Eos will utilize a systems approach in its measurement and sampling strategy. This approach calls for altimetry to measure meso- to large-scale surface geostrophic currents and scatterometry to measure ocean surface winds that ultimately drive ocean currents. Eos will also provide measurements of other sea surface parameters, including roughness (SAR), wave height (ALT), temperature (MODIS and AMSR), and ocean color (MODIS). These observations will be incorporated in an overall synergistic strategy for ocean observations, the Eos strategy.

As an example, an international, large-scale oceanographic experiment is planned for the next decade; it is the World Ocean Circulation Experiment

(WOCE). The major scientific goal of WOCE is to understand the general circulation of the global ocean well enough to be able to model its present state and predict its evolution in relation to long-term changes in the atmosphere (U.S. WOCE Science Steering Committee, 1986). This goal falls well within Eos scientific objectives and therefore the oceanographic component of Eos can be viewed as highly complementary to WOCE efforts, the ultimate goal being understanding the ocean's role in climate changes. Perhaps the single most effective means of assessing the ocean's role is via its general circulation. It, in turn, is addressable through long-term measurements of surface elevation using satellite altimetric techniques.

Among the various oceanographic measurement techniques, altimetry is a relatively well-developed one. The technologic and scientific results have been well documented. A brief discussion on its applications to oceanography is given below, followed by a rationale for the Eos altimetry system and its objectives and requirements for oceanographic research. Finally, aspects of the developing technique of multibeam altimetry are briefly discussed.

Oceanographic Applications

A satellite altimeter measures its altitude above sea surface (denoted by h in Figure 1) through pulse ranging. With the height of the satellite (orbit height, denoted by r) relative to the center of mass of the Earth determined by independent tracking and modeling, the sea surface elevation (denoted by s) can

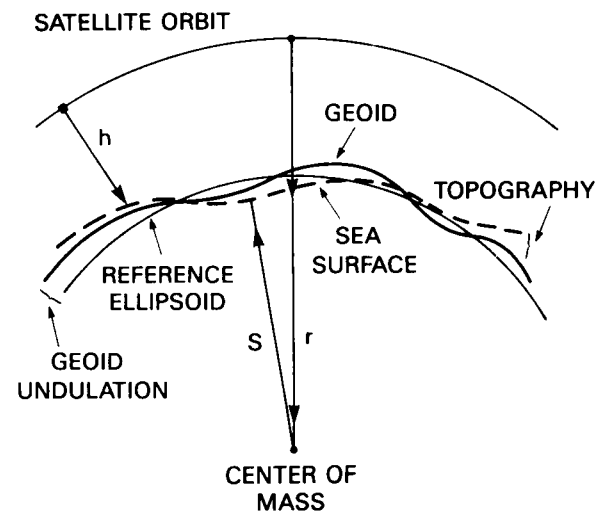


Figure 1. Observation geometry (from Stewart, 1985).

then be readily obtained from altimetric measurement. The measurement of sea surface elevation is one of the most useful oceanographic measurements that can be made from space because the ocean topography, the difference between sea surface elevation and the geoid, is directly related to the surface geostrophic current velocity that can be used to compute deep current velocity through its relationship with the ocean density field. Wunsch and Gaposchkin (1980) and Stewart (1985) summarize these principles of satellite altimetry.

In addition to sea surface elevation, an altimeter can measure sea surface wind speed and wave height by means of the measurement of the strength and shape, respectively, of the return pulse. A brief discussion of these three applications of satellite altimetry is given below.

Sea Surface Elevation

The first demonstration of the usefulness of altimetric measurement of sea surface elevation for observing ocean currents was made by the GEOS-3 mission (e.g., Huang *et al.*, 1978). Its nearly continuous 3½ years (1975-1978) of data collected in the western North Atlantic allowed a first look at the long-term variability of ocean currents from a spaceborne altimeter. Displayed in Figure 2 is a recent result from the GEOS-3 data (Fu *et al.*, 1986), showing the seasonal and interannual variability of the Gulf Stream surface current. Understanding long-term variability of ocean currents is a key step in assessing the ocean's role in the Earth system.

The Seasat altimeter made high quality, global observations of the sea surface topography and its variability (see Fu, 1983, for a review). Shown in Figure 3 is a global map of the oceanic mesoscale variability derived from 1 month of Seasat data (Cheney *et al.*, 1983). Qualitatively, this map is consistent with the eddy energy map made by Wyrтки *et al.* (1976) using 70 years of ship drift data. By making global, continuous altimetric measurements, we can obtain a detailed description of the global mesoscale variability in frequency/wavenumber space.

Wind Speed and Wave Height

These two measurements will be useful for improving our forecasting capabilities of ocean waves and storm surges. Mognard *et al.* (1983) have already demonstrated the usefulness of Seasat wind speed and wave height measurements in describing sea state. The main obstacle in improving our ocean-waves forecasting skills is the lack of simultaneous global observations of winds and waves to test, refine, initialize, and update wave-prediction models. The measurements of significant wave height and wind speed from satellite altimetry, combined with wind vectors measured by scatterometry, will provide a valuable data base for improving wave forecasting skills.

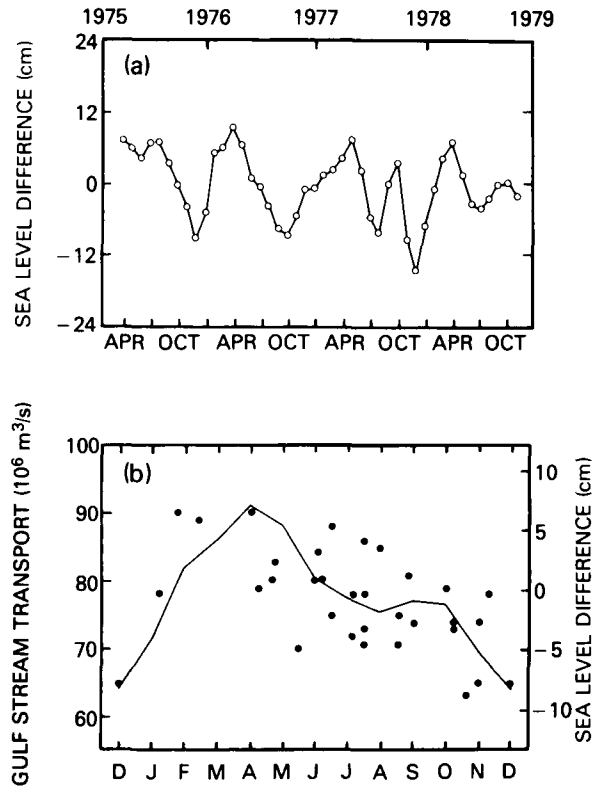


Figure 2. (a) Sea level difference across the Gulf Stream (south minus north) near 73°W. The mean has been removed. (b) The solid line represents the annual variation of the sea level difference across the Gulf Stream (values in (a) averaged by the months of the year). The dots represent an assemblage of *in situ* measurements of the transport of the Gulf Stream relative to a depth of 2,000 m (from Fu *et al.*, 1986).

Storm surges, the substantial rises in sea level produced by shoreward storm winds over shallow coastal waters, 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, tidal phase, bathymetric relief, and currents. Altimetry offers simultaneous measurement of current, winds, and wave height for these studies.

Altimetry Systems

A summary comparison of the accuracies in measuring sea surface elevations from GEOS-3, Seasat, and TOPEX/Poseidon is presented in Table 1. From this comparison, we clearly see the potential for yet higher precision data; the expected high quality of TOPEX/Poseidon data affords a means for substantially improving our understanding of the dynamics of global ocean circulation.

The maximum life of the TOPEX/Poseidon spacecraft is expected to be about 5 years, too short

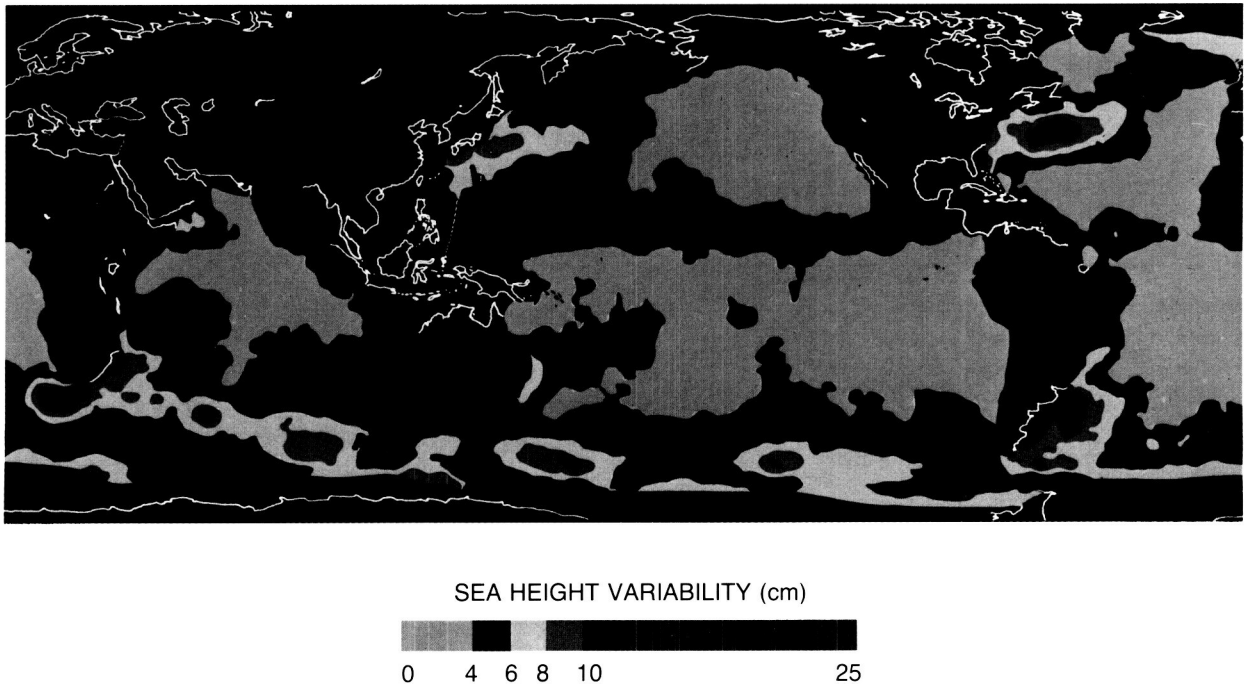


Figure 3. Sea surface height variability from Seasat altimeter data. Contour interval is 1 cm (from Cheney *et al.* 1983).

to characterize interannual variability in the ocean. The Eos altimetric system therefore should be designed to make measurements with quality comparable to or exceeding that of TOPEX/Poseidon, extending the high-quality altimetric measurements over decadal time scales for climate studies.

Table 1. Error Summary of Altimetric Systems (cm)

	GEOS-3	Seasat	TOPEX/ Poseidon*
Instrument Error	25	5	2
Media Error**	10–50	10–20	4
Orbit Error	200–1,000	100	13

*Estimates based on current project plans and instrument definition.

**Including effects of electromagnetic bias, wave skewness, tropospheric water vapor, and ionospheric electrons.

There are two potential legacies of the TOPEX/Poseidon mission that can be used advantageously in the planning of the Eos altimetric system. The first is the precise measurements of ocean tides. With much improved knowledge of ocean tides, there is little need to worry about sun-synchronous orbits and low-frequency solar-tidal aliasing. The second is the GPS tracking technology to be developed by TOPEX/Poseidon. This development will enhance our ability

to determine the precise orbit of spacecraft with much less effort.

Due to the competing sampling requirements in space and time, a single altimeter such as planned for TOPEX/Poseidon cannot adequately resolve the two-dimensional structure of mesoscale eddies (*viz.* Bernstein *et al.*, 1979). For example, the ground track separation of TOPEX/Poseidon is about 300 km at the equator. However, this could be achieved by either multiple TOPEX-class altimeters (one being deployed on each of the Eos platforms) or with the technique of multibeam altimetry (Bush *et al.*, 1984). In principle, multibeam altimetry allows the generation of a finite swath (~100 km) of altimetry observations along the ground trace, thereby mapping mesoscale eddies. As part of the Eos altimetry program, the development of this new multibeam concept should be fostered.

It has been shown that off-nadir (*i.e.*, multibeam) altimetry measurements are extremely sensitive to altimeter pointing errors (Bush *et al.*, 1984). Thus, a robust variable that could be measured is not sea surface elevation but rather its curvature: in essence, the vorticity of the surface geostrophic current (Lee and Parsons, 1986). Vorticity is an extremely useful parameter for describing large-scale geostrophic flows (see Pedlosky, 1979) but it is virtually impossible to measure by conventional methods. A typical mid-ocean eddy would have a velocity scale of 20 cm/s varying over about 100 km, corresponding to a vorticity of $2 \times 10^{-6} \text{ s}^{-1}$. Sufficiently accurate

multibeam altimetry would thus afford an entirely new capability, the ability to measure vorticity of the mesoscale field directly.

A secondary objective of the Eos altimetry program should be directed toward the development of multibeam altimetry technology for making off-nadir altimetry measurements to map oceanic mesoscale eddies. We therefore recommend that a prototype system be developed and tested.

Measurement Requirements

The primary oceanographic objective for the Eos altimeter system is to make multiyear observations of sea surface elevation, wind speed, and wave height with data quality comparable to that of the TOPEX/Poseidon mission. Following is a set of minimum requirements for achieving this objective.

- The altimeter should have two channels to make corrections for the effects of ionospheric free electrons.
- The altimeter system should be deployed with AMSR (or some other TOPEX-class microwave radiometer), which would provide corrections for tropospheric water vapor effects.
- A high-precision tracking system (e.g., GPS and GLRS) is required to satisfy the precision orbit determination needs (nominally, the radial component of the orbit must be known with an accuracy of 10 to 20 cm).
- Depending upon the exact configuration of the instrument to be deployed, consideration should be given to attitude compensation/control and measurement. This may have impact on the overall spacecraft design.
- The spacecraft ground trace must repeat with a root-mean-square error of 1 km. This requirement may be relaxed if the knowledge of the marine geoid is much improved by the Geophysical Research Mission (GRM) or an equivalent effort.
- The ground trace repeat period should be between 10 and 20 days.
- There should be a carefully designed and documented data verification and calibration plan that should be implemented at launch.
- Accuracy and precision of the overall altimetric height measurement should be equivalent to or exceed those expected from the TOPEX/Poseidon spacecraft.

GEOPHYSICS

Geodetic observations over the oceans fall into broad categories: those relating to marine gravity and

those relating to the precise determination of points on the ocean floor. Sea surface gravity measurements have the longest history of any oceanic geodetic measurement. They are motivated by the insight they provide into the structure of ocean crust and the buildup of strain and tilt at the seafloor. Thus, they form an essential component in our understanding of the dynamics of crustal processes.

Since 1975 when the first dedicated satellite altimeter was placed in orbit, the spaceborne altimeter has become one of the primary tools for measuring the global marine gravity field. In addition to the scientific contributions to the area of oceanography, the data collected by altimeters have provided a completely new perspective of the marine geoid and a substantial improvement in our knowledge of ocean bathymetry. Furthermore, satellite altimetric data sets have been used to improve global models for the Earth's gravity field. The proposed spaceborne altimetry system on Eos platforms could greatly enhance the ability of geophysical mapping of the Earth. With increases in accuracy and resolution, it will provide substantial contributions to several areas of marine geodesy and geophysics.

Global Mean Ocean Surface

Altimetric data have been used as height data to create global, mean ocean surfaces. When the mean sea surfaces are corrected for the effects of ocean surface steric anomalies, the result will, to a first approximation, agree with the marine geoid. The capability of satellite-borne altimetry to globally map the instantaneous sea surface provides a powerful technique for marine geoid determination. The Seasat and GEOS-3 altimeter data can be used to produce a mean ocean surface with roughness and spectra for short wavelength (<220 km) surface features. With the inclusion of Geosat data and data from future spaceborne altimeters, greater resolution of the altimetric sea surface is expected.

For example, altimetric sea surfaces have been developed by Schutz *et al.* (1985), Marsh *et al.* (1984), and Haxby *et al.* (1983). Schutz *et al.* (1985) computed a mean ocean surface using 18 days of Seasat altimeter data (Shum, 1983; Schutz *et al.*, 1985). The spatial data distribution of the altimeter data set used in their analysis is shown in Figure 4. The data in the 18-day orbit provides a resolution of about 1.5° at the equator. Their mean ocean surface was precisely determined with an accuracy of 48 cm rms.

Earth's Gravity Field and Tidal Response

Direct altimeter crossover data have proven useful in the determination of both long- and short-wavelength features of the Earth's gravity field and its tidal response. The altimeter height and crossover data, when modeled as a global measure of the geoid,

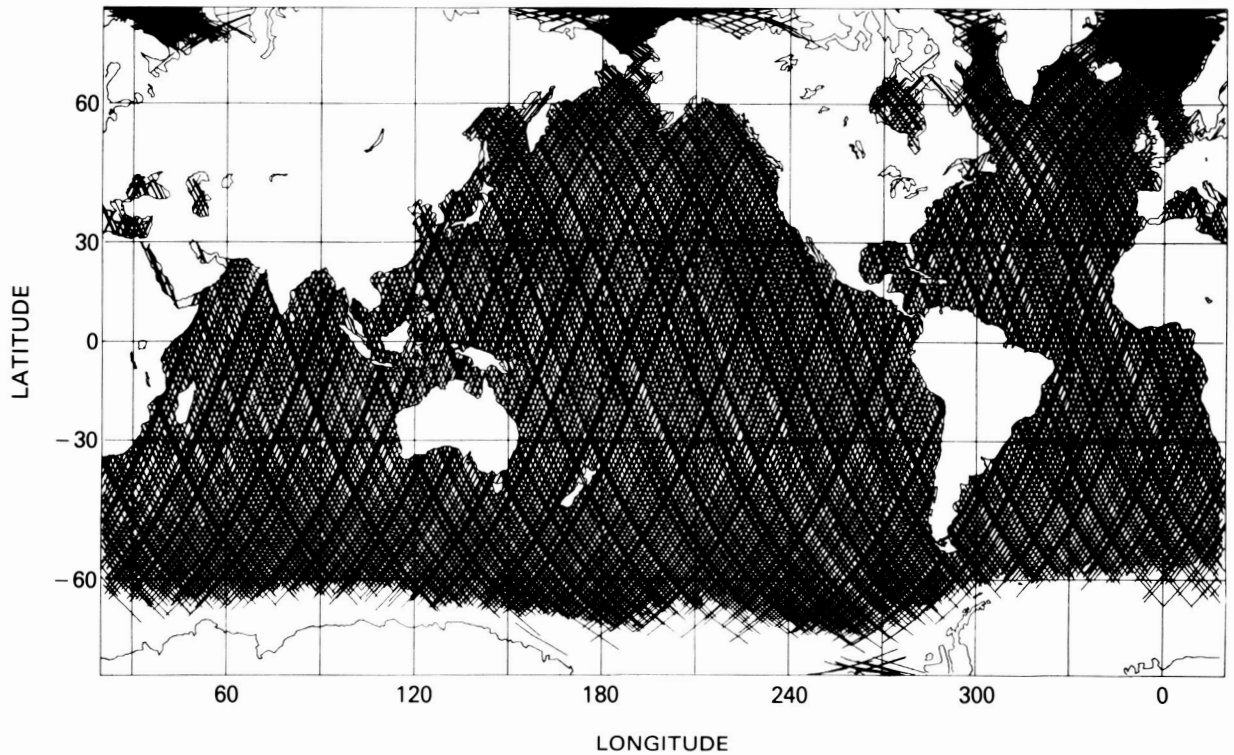


Figure 4. Seasat 18-day arc altimeter data distribution.

are excellent tools for determining perturbation of the Earth's geopotential field and long period solid-Earth and ocean tides. Figure 5 shows the cumulative geoid undulation accuracy for several gravity field models, excluding and including satellite altimetric data, the expected accuracy for the TOPEX/Poseidon gravity field, and finally the estimated precision of the Earth's gravity field after GRM. Altimeter data provide the means for determining the Earth's gravity field to an accuracy needed to achieve the orbit accuracy requirement for TOPEX/Poseidon, hence Eos. With the availability of altimeter measurements over a lengthy period of time and with abundance of spatial coverage, the direct measurement of tidal heights and the construction of global, high-resolution tide charts are possible.

Accurate determination of the gravity field using orbital motions of artificial satellites requires spacecraft with various inclinations and different altitudes. This requirement is essential since the spatial variation of the spherical harmonic geopotential coefficients (in terms of frequencies) cannot be separated if only one satellite is used. Furthermore, conventional tracking data (i.e., laser ranging or doppler data) do not provide continuous satellite coverage, making the determination of higher degree and order geopotential coefficients difficult.

Satellite-borne radar altimeters provide an additional tool to map the Earth's gravity field. The ability of these instruments to globally measure the ocean surface with high accuracy constitutes a unique data

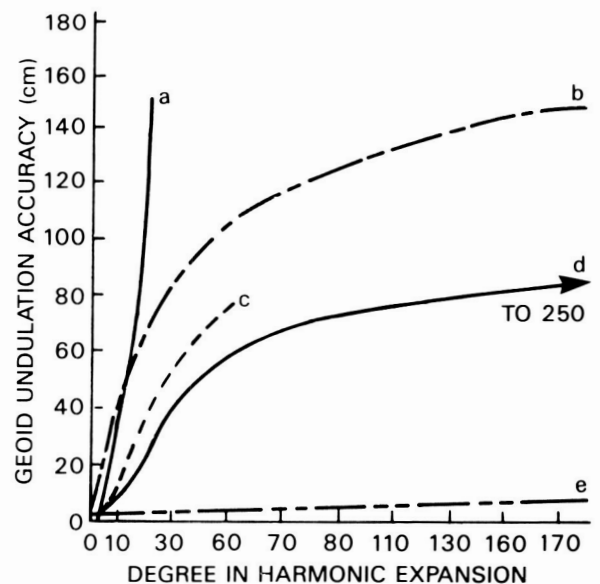


Figure 5. Cumulative geoid undulation accuracy: (a) present "satellite" models (GEM-L2); (b) present satellite models with the addition of altimetric data (GEM-10C, OSU-B2); (c) estimate based upon preliminary TOPEX model; (d) estimated potential accuracy based upon a refined TOPEX model; (e) estimate based upon the Geodynamics Research Mission.

set for gravity field determination. The gravity field determined solely with measurements from one

altimetric spacecraft, however, will be skewed toward the oceanic area, since the altimeter observations provide gravity information only for the oceanic area. Nevertheless, the solution for a relatively accurate gravity field is possible using only one altimetric satellite in low Earth orbit; it is not restricted by the multiple spacecraft requirement discussed above.

The conventional approach using altimeter-derived information combines these data into the gravity field normal matrix in the form of either geoid undulations or gravity anomaly. This approach is similar to that of using the terrestrial gravity data, which is applied as geometrical constraints to the gravity solution (viz. Rapp, 1984). An alternate technique involves the direct use of altimeter data and altimeter crossing arc data in a dynamically consistent manner to solve for the Earth's gravity field, tides, and sea surface topography.

A model of the altimeter height measurement can be developed based upon a model of the global ocean surface, which can be separated into a static and a dynamic component. The static component includes the geoid (which can be modeled by an equipotential surface of the Earth's geopotential field) surrounded by the Earth's rotating atmosphere, the rotational potential of the Earth, and a model of the stationary sea surface topography (which represents a permanent departure of the ocean surface from the geoid). The stationary sea surface topography consists of oceanic currents as well as systematic seasonal steric anomalies averaged over an extended period of time. The dynamic component of the ocean surface consists of time-varying departures from the geoid, which include the periodic variation in the ocean surface due to solid Earth and ocean tidal perturbations and the time-dependent sea surface topography.

In this model, altimeter height measurement can be computed by modeling a static geoid surface mathematically, providing that the dynamic component of the ocean surface is adequately modeled. In fact, with the exception of the time-dependent topography, solid Earth and ocean tidal effects can be modeled dynamically with spherical harmonics of the Earth's geopotential field and geometrically by applying tidal corrections to the altimeter height. The dynamical effect of the time-varying surface topography can be neglected due to its small magnitude. Based on the assumptions that (1) the model of the equipotential surface includes the influence of atmosphere as well as the indistinguishable stationary sea surface topography, and (2) that the direction of the altimeter measurement is along the geodetic vertical or the local normal at the subsatellite point, relations between the ocean surface and the subsatellite point can be established. Any dynamical affect is evidenced through its influence on the geopotential field, which in turn determines the position of the satellite in space. In fact, the application of the altimeter data for the solution of a Seasat-tailored gravity field has proven quite powerful in yielding precise

ephemerides along the altimeter ground trace in oceanic areas (Shum, 1983; Schutz *et al.*, 1985).

A gravity field model (designated UTGF26), that was derived using Seasat laser and altimeter data, is complete to degree and order 26 of spherical harmonic coefficients and is augmented by the GSFC gravity field model (PGS-S4) for coefficients above 26×26 . The resulting Seasat 18-day ephemeris has an estimated radial orbit accuracy of ± 34 cm (inferred by the root-mean-square altimeter crossover differences). A global contour map of geoid heights computed using UTGF26 is shown in Figure 6a. Figure 6b shows a contour map of geoid height difference between the PGS-S4 and UTGF26 gravity fields. Significant differences occur only in continental areas and in regions where satellite tracking and altimeter data were not available. However, in the oceanic area where altimeter data are abundant, the geoid height difference between the two gravity fields is on the order of 1 m. While the PGS-S4 field was derived using data collected by over 20 satellites as well as altimeter data, the UTGF26 was determined using only Seasat data. Thus, the performance of UTGF26 in the determination of an accurate Seasat orbit strongly suggested the importance of the altimeter data for gravity solutions.

Although a satellite-borne altimeter has a distinct advantage in its global distribution of data, consideration of possible error sources when altimeter data are used for orbit determination suggests several disadvantages. In particular, long-wavelength oceanographic features and relatively static ocean topography can be absorbed into the orbit when altimeter data are directly used for orbit and geodetic parameter determination. Static topography, mostly due to error in the global geoid, has uncertainty of several meters and is significant when decimeter radial orbit accuracy is desired. A technique that eliminates the altimeter dependence on the non-temporal topography is the use of altimeter measurements at the points where orbit ground traces intersect. These points are referred to as "crossover points," and the differences of altimeter measurements at these points are referred to as "crossover measurements" or "residuals." Collectively, crossovers have been valuable for the evaluation of radial orbit ephemeris error. Although the non-temporal portion of the ocean topography can be eliminated at a crossover point, the remaining temporal changes, (e.g., ocean tide, unmodeled orbit error, short-wavelength phenomena, as well as altimeter time tag error) can still be aliased into the radial orbit error on a global basis. With the exception of the geographically correlated error due to inaccuracy in the Earth's gravity field, global computation and analysis of crossover residuals can provide valuable information about radial orbit error sources.

Crossover measurements also represent a unique data set for orbit determination both in their geometry and since any error sources common to the crossing point cancel out. Orbit determination experiments

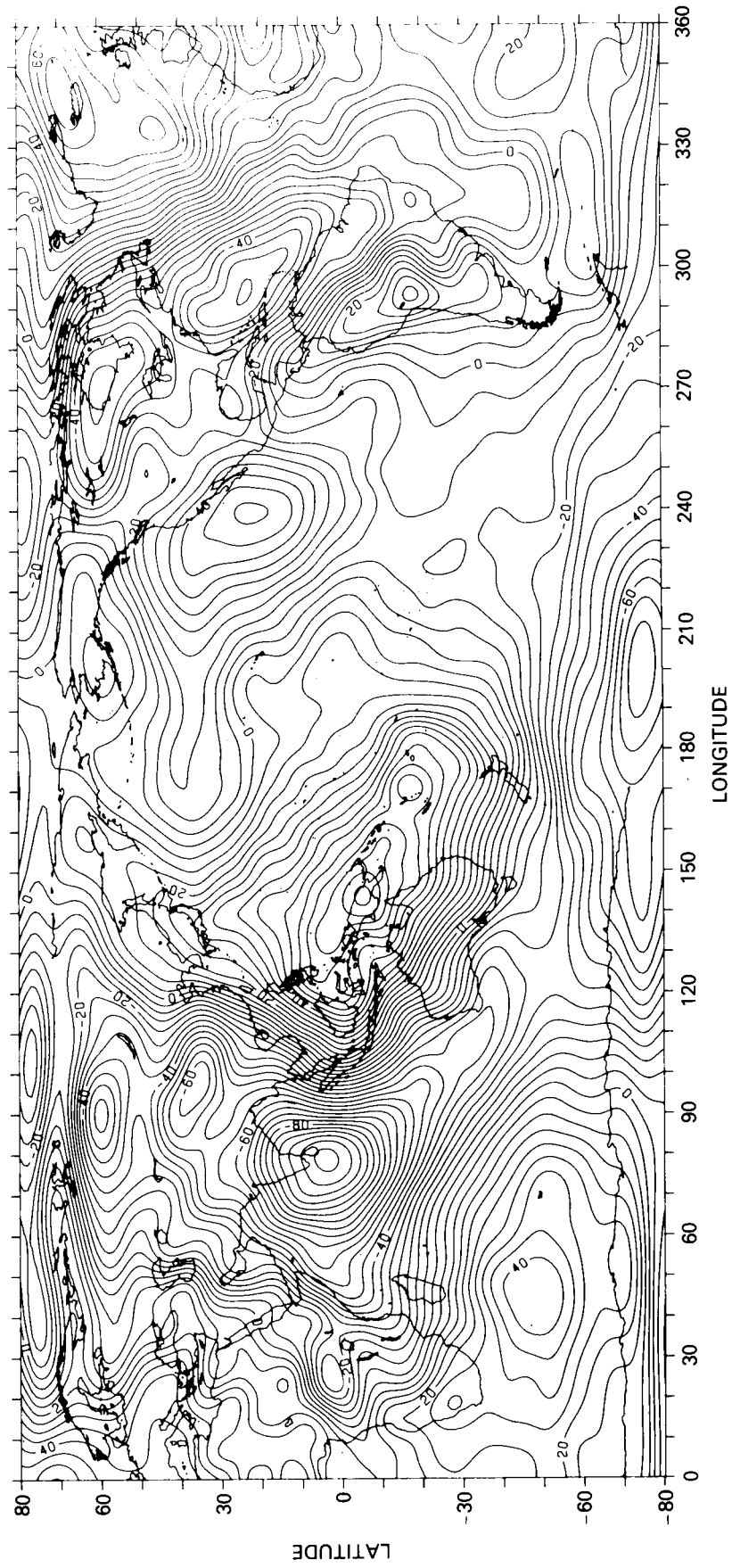


Figure 6. (a) Geoid height computed with the University of Texas UTGF26 model. Contour intervals are at 5 m.

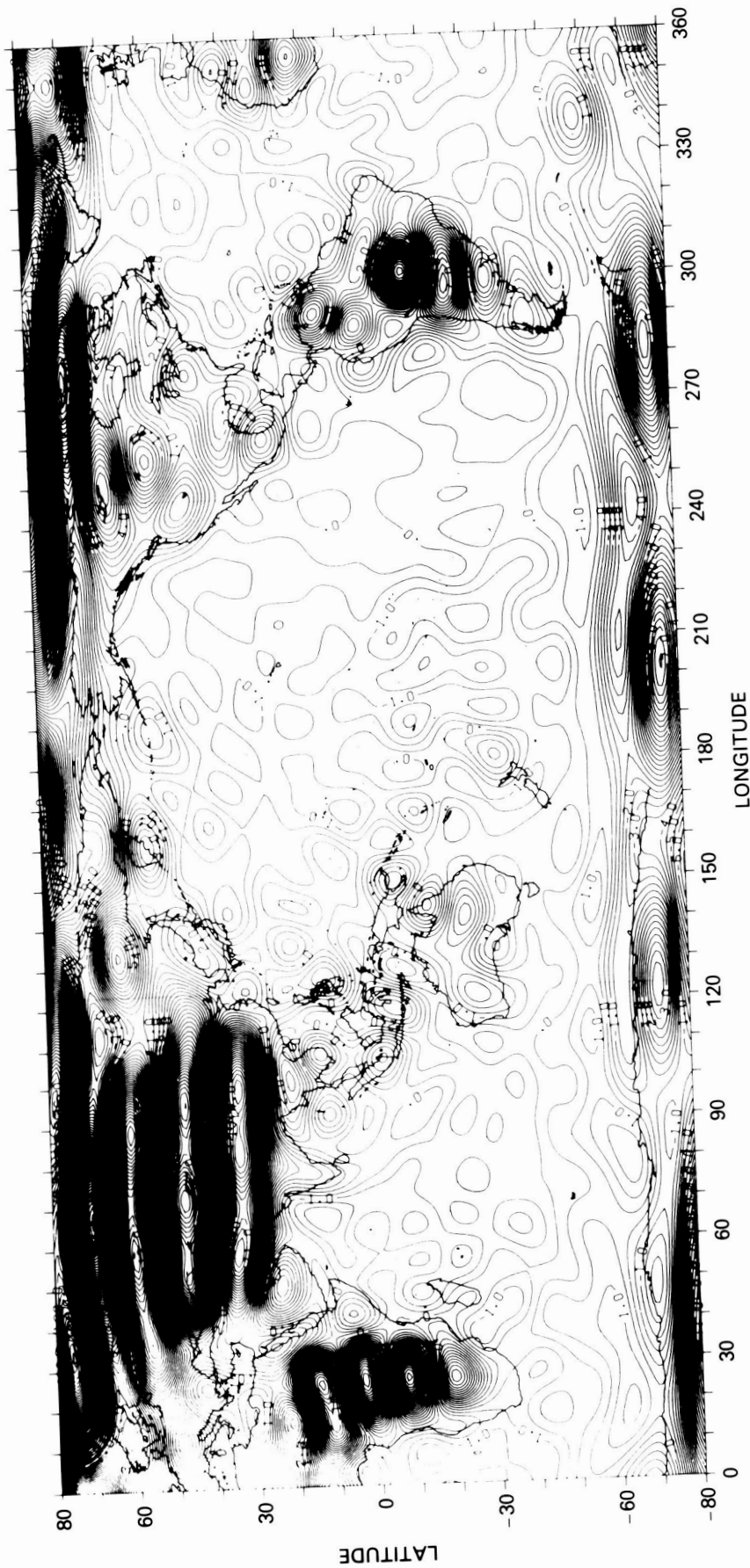


Figure 6. (b) Differences in geoid heights between the Goddard Space Flight Center (PGS-S4) and University of Texas (UTGF26) gravity field models; contour intervals are 0.5 m.

using Seasat altimeter crossover data show significant improvement in orbit accuracy when altimeter crossover data are used in conjunction with other types of conventional data. Altimeter crossover data, when used in gravity field solution, have an advantage over the direct use of altimeter data in that the inaccurate modeling of the ocean surface topography will not be aliased into gravity information. The crossover data also have excellent coverage over the global ocean. Research work involving the use of dual- or multiple-crossover altimetry suggests new techniques in the use of altimeter data for orbit determination and for application in geodynamics (for example, determination of the Earth's gravity field).

Charting of the Ocean Basins

Satellite altimetry has been used to observe bathymetric features, including the mid-ocean ridges, trenches, fracture zones, plateaus, and seamount chains. Since geoid anomalies decrease slowly from a mass anomaly, the shape of the geoid reflects the distribution of relatively deep-seated mass within the Earth. The vertical gradient of the gravity field potential decreases more rapidly and hence is more sensitive to shallow mass anomalies. Nevertheless, major contributions to the marine geoid are made by topographic anomalies in the shallow rock-water interfaces. Thus, there is a strong correlation between ocean surface shape and bottom topography (bathymetry).

Altimeter data are useful in the determination of general, or broad-scale, sea floor bathymetry. The long-wavelength geoid correlates with the geoid inferred by density variation calculated using seismic data. The ratio of geoid height to bottom topography is sensitive to the strength of the oceanic lithosphere when seamounts (or undersea volcanoes) are formed. Global altimeter data provide a means to survey the relatively uncharted seamount population density and provide information (in terms of geoid height signatures) to estimate the strength of the lithosphere when these seamounts were formed.

Satellite altimetry has become an important reconnaissance and mapping tool for marine geophysicists. While most northern hemisphere oceanic areas have been surveyed by research vessels, there are large areas of the southern ocean basins that remain unexplored. Satellite altimetry has been used to discover many large features in these remote areas. For example, detailed images of the marine geoid, derived from GEOS-3 and Seasat radar altimeter profiles, reveal that the 6,000 km long Eltanin Fracture Zone/Louisville Ridge System produces a continuous geoid signature across most of the South Pacific. Moreover, hundreds of previously uncharted seamounts have been discovered in satellite altimeter data, including a group of the South Central Pacific (latitude 30°S to 40°S by 115°W to 135°W). In the next decade, planned altimeter missions (e.g., Geosat

17-day repeat, ERS-1 and TOPEX) will further increase our resolution of the sea surface topography by a factor of 10. Geoid undulations with wavelengths as short as 20 km and amplitudes of 0.1 m will be completely mapped over all ocean basins. These new data, in conjunction with image enhancement techniques, will provide a new view of the southern ocean basins. One of the important contributions of a satellite altimeter onboard the Eos will be the collection of data in high latitudes during ice-free periods.

An illustration of why satellite altimeters are an important mapping tool is shown in Figure 7. The upper image (Figure 7a) is the geoid height map for the Gulf of Mexico and the Caribbean Sea generated by combining altimeter data collected by GEOS-3 and Seasat. It was constructed using a new technique that finds the minimum curvature surface that matches along-track geoid slopes from all of the satellite passes (Sandwell, 1986). The marine geoid map was illuminated from the northeast to enhance the shorter-wavelength geoid undulations. A comparison between the geoid surface and the bathymetry (Figure 7b) shows high correlation between the two surfaces, especially at the shortest wavelengths. Even though the Gulf and the Caribbean are well surveyed, the geoid map constructed using altimetry reveals some new features. First, while the topography of the Cayman Trough is symmetric about the center of the trough, the geoid is asymmetric. Slopes in the geoid are much higher along the active transform faults than they are along the passive fracture zones. Second, the geoid shows a previously undiscovered lineation parallel to the Beata Ridge that extends from Costa Rica to the eastern edge of Jamaica. Finally, the Atlantic fracture zones are evident in the geoid even though some of the fracture zone is buried by sediments.

Marine Gravity and Geophysics

The altimeter data can be used to determine local deflections of the vertical along the ground trace of a satellite. This information is related to the derivative of the along-trace height measurements and as such will be particularly sensitive to the short wavelength variations in the marine geoid. The deflection of the vertical is particularly useful in studying the oceanic lithosphere and in describing boundaries and fracture zones in oceanic plates. Gravity anomalies can also be inferred from the altimeter data.

Undulations of the mean sea surface, or the (nearly identical) geoid, are caused primarily by lateral density inhomogeneities within the Earth. These mass anomalies are physically supported by deviatoric stresses arising either from convective motions of the viscous mantle or from static loads on the rigid lithosphere. Mantle-wide convection maintains many of the longer wavelength ($>10^6$ m), larger amplitude (>10 m) geoid undulations (Kaula, 1972).

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

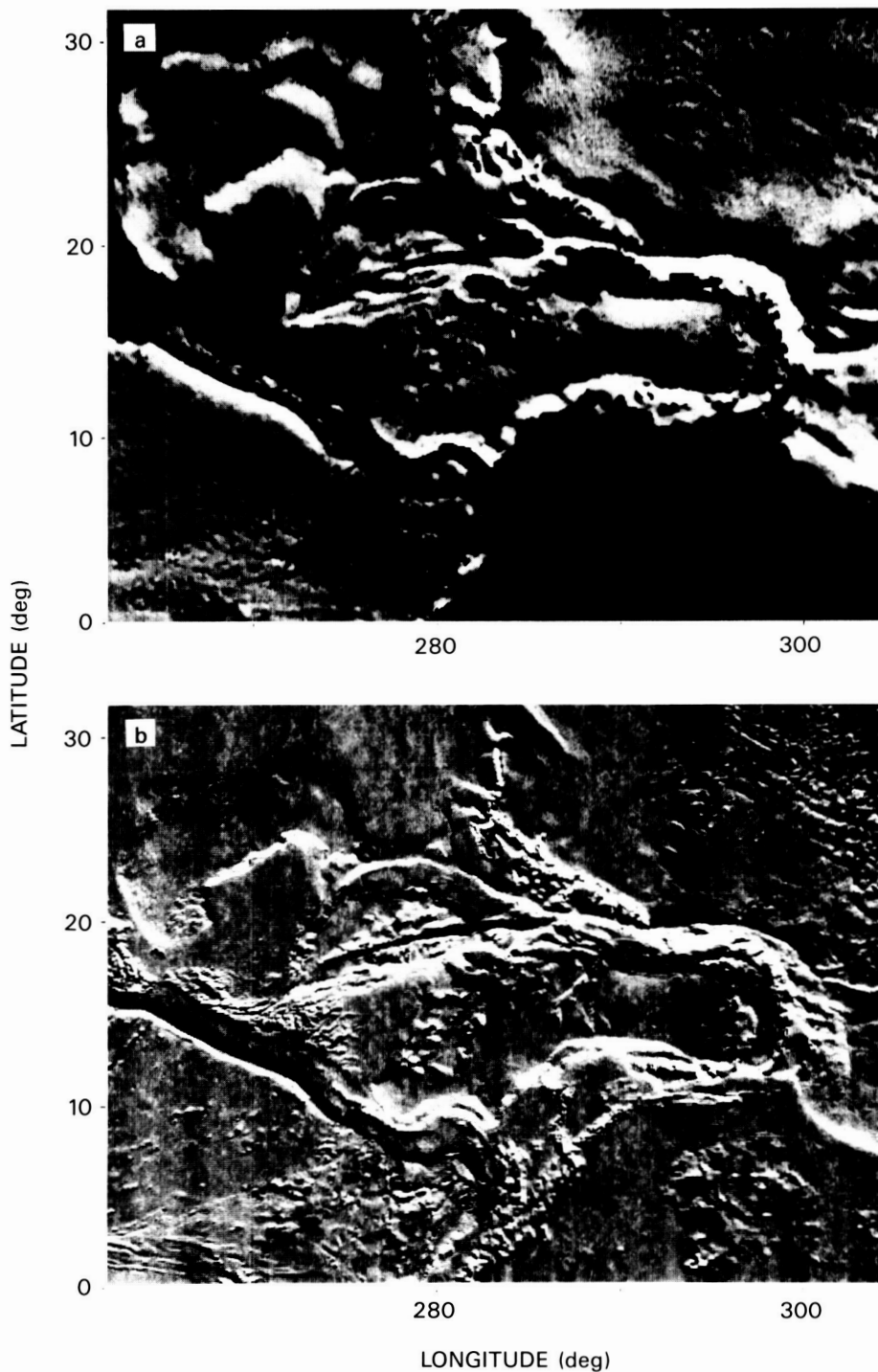


Figure 7. Shaded relief maps of geoid height (a) and bathymetry (b) covering Central America. The bathymetry and land topography were derived from terrestrial observations and compiled onto a 5' grid by J. Heitzler *et al.* of Woods Hole Oceanographic Institution, Woods Hole, MA (see *Eos*, March 11, 1986 cover). The geoid height, on a 5' Mercator grid, was constructed from GEOS-3 and Seasat satellite altimeter data. The more accurate but less dense Seasat data control the accuracy of the geoid map, while the less accurate but more dense GEOS-3 data control the detail in the map. In this area there is a high correlation between geoid height and topography, suggesting that satellite altimeters can be used to map the ocean basins. In most other areas, however, the satellite altimeter coverage is insufficient to reveal all of the details in the seafloor topography.

Indeed, a number of studies point out the high correlation between geoid undulation and surface manifestations of mantle convection such as spreading ridges, subduction zones, and hot-spot swells (Haxby and Turcotte, 1978; Sandwell and Schubert, 1982; Griggs, 1972; Hager, 1984; Crough and Jurdy, 1980).

Although the geoid is dominated by these longer-wavelength undulations, much information is contained in the shorter-wavelength ($\ll 10^6$ m) signals. These primarily originate from density anomalies within the lithosphere. In all but a few extreme cases, shorter-wavelength geoid undulations are highly correlated with seafloor topography. The high resolution and accuracy of the Seasat radar altimeter provides a global view of these shorter-wavelength geoid undulations.

The most prominent seafloor features reflected in the sea surface topography are trenches, fracture zones, large seamounts, and spreading ridges. Examples of Seasat profiles across trenches and oceanic fracture zones are presented in Figure 8 along with physical models of these features. Other examples of altimeter profiles over seamounts and spreading ridges are presented in papers by Haxby and Turcotte (1978) and Watts and Ribe (1984). In general, satellite altimeter data are particularly suited to geophysical studies of long, linear features like trenches, outer rises, or fracture zones, because these data enjoy the advantage of geoidal representation in which unmodeled, local, short-wavelength effects (e.g., seamounts) are attenuated.

The shape of the marine geoid at shorter spatial wavelengths is predominantly a smoothed, attenuated version of seafloor topography (see Chapman, 1979). It is, therefore, not surprising that deep-ocean trenches (and the outer rises that flank them) appear in the marine geoid and are readily observed by satellite altimeters. In fact, the deep-ocean trenches represent the largest amplitude undulations in the marine geoid exclusive of very long (>400 km) wavelengths. The Aleutian trench, for example, contributes 15 m of relief. Trenches manifest themselves so clearly in the geoid because they are paramount bathymetric features and they are not, to a large degree, isostatically compensated (Vening Meinesz, 1964).

Outer rises lying just seaward of most deep-ocean trenches also are isostatically uncompensated features (Watts and Talwani, 1974; McAdoo and Martin, 1984). These have wavelengths (transverse to trench axes) of several hundred kilometers and contribute as much as 6 m of relief to the marine geoid. They are attributable to flexure of the oceanic lithosphere prior to subduction. This flexure is generally modeled by representing the oceanic lithosphere as an end-loaded elastic plate. An elastic model of lithospheric deflection predicts the topographic shape for the outer rise and outer wall of the trench. It can be extended to predict concomitant geoid undulations. An approximate, analytical ex-

pression for these predicted geoid undulations is derived in McAdoo and Martin (1984). This enables predicted geoid undulations to be compared with individual satellite altimeter transects over outer rises. First, the data are high-pass filtered by removing a reference geoid. By using the method of least squares, elastic model parameters such as flexural wavelength can be estimated for each altimeter transect.

Two Seasat transects, an ascending pass over the southern Mariana Trench and a descending pass across the South Sandwich Trench, are shown in Figure 8 (note that available bathymetric data across these trenches are not suitable for studies such as this). Estimates of flexural wavelength can be converted to estimates of lithospheric thickness. In McAdoo and Martin (1984) and McAdoo *et al.* (1984), Seasat altimeter data over various outer rises are used to demonstrate that the mechanical lithosphere thickens with age in a manner consistent with established thermal models (e.g., Parsons and Sclater, 1977) and can achieve a thickness as great as 60 or 70 km. Consequently, altimetric data significantly augment available information concerning the shapes

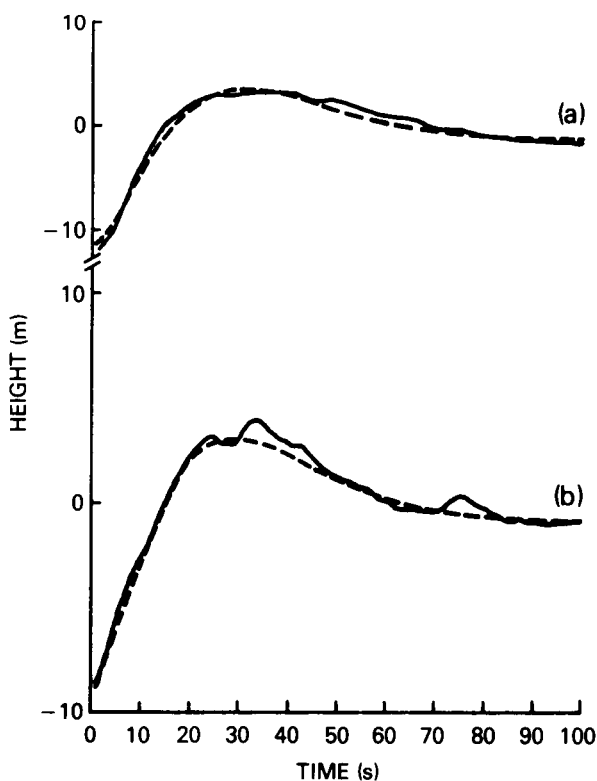


Figure 8. Individual Seasat passes (low-cut filtered) across two trenches. Shown as dashed curves are best-fitting geoid profiles generated by an elastic lithosphere model. (a) South Sandwich Trench, $\phi = -55.60^\circ$, $Rev = 468$, $\alpha = 105.5 \pm 4.3$, $W_0 = 1,975 \pm 94$. (b) Southern Mariana Trench, $\phi = 10.85^\circ$, $\lambda = 140.92^\circ$, $Rev = 829$, $\alpha = 103.1 \pm 5.3$, $W_0 = 1,683 \pm 10$.

of outer rises and regional variations in the thickness of the lithosphere.

Fracture zones are linear scars in the seafloor produced by transform faulting (Wilson, 1965). Topography along their inactive segments consists of long ridges, troughs, and scarps separating regions of different depth (Menard and Atwater, 1969). Fracture zones are formed as part of the seafloor spreading process. Spreading ridges generally consist of short segments (50 to 500 km) offset by transform faults. Strike-slip motion occurs along the transform fault, producing fractures in the seafloor. Once the lithosphere migrates beyond the intersection of the spreading ridge with the transform fault, the two sections of lithosphere move at the same rate and eventually become welded together. The fractured seafloor remains along this older section of the fracture zone although no new fractures develop.

Results from a physical model for the thermomechanical evolution of a fracture zone are shown in Figure 9 (Sandwell, 1984). Figure 9a shows the development of the ridge and trough topography across a large age-offset fracture zone (i.e., 20 Ma age offset). Since the younger lithosphere subsides at a higher rate than the older lithosphere, the ridge and trough signature develops in just a few million years. This flexural topography extends to about 100 km on either side of the fracture zone.

The same model is used to predict the geoid step (Figure 9c) and the geoid slope (Figure 9b) across a fracture zone. The geoid step has an amplitude of 3 m, while maximum geoid slopes (i.e., deflections of the vertical) are $80 \mu\text{rad}$. As the fracture zone evolves, the geoid step becomes complex, reflecting the development of the ridge and trough topography. The deflection of the vertical, rather than the geoid profile, is compared with the data because differentiation of the altimeter profile removes the long-wavelength, large-amplitude components of the geoid that are associated with density anomalies in the mantle.

Large values of the deflection of the vertical ($\sim 50 \text{ rad} = 10 \text{ arcsec}$) occur along the Udintsev fracture zone because of its large age offset ($\sim 18 \text{ Ma}$; Weissel *et al.*, 1977). Examples of along-track deflection of the vertical profiles, computed by differentiating a subset of descending Seasat altimeter passes, are shown in Figure 10. On this projection, the Heezen, Tharp, and Udintsev transform faults are shown as heavy horizontal lines, whereas segments of the Pacific-Antarctic spreading ridge appear as heavy vertical lines. Deflections of the vertical along the Udintsev fracture zone (i.e., filled profiles in Figure 10) show a simple systematic pattern. At the midpoint between the two spreading ridges, a positive peak lies to the north of the transform fault, while a negative peak lies to the south. At the left ridge-transform intersection, there is only a positive peak. Further to the left, along the inactive portion of the fracture zone, there is a positive peak centered

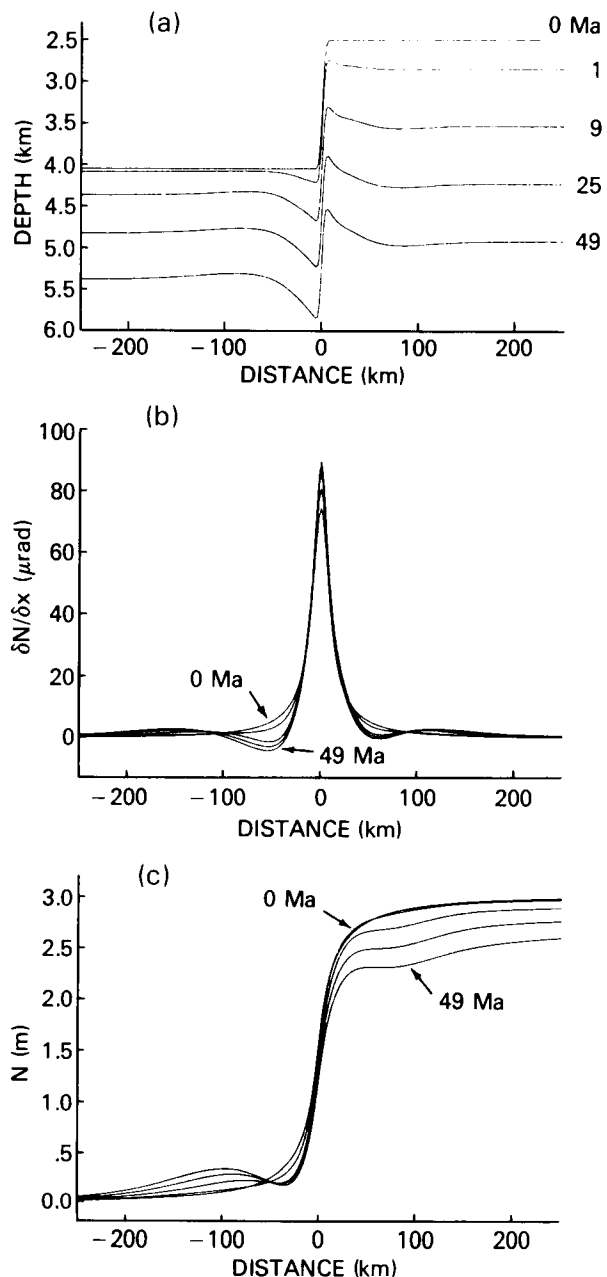


Figure 9. Evolution of an FZ (20 Ma age offset) from a thermomechanical model. (a) Topography within a few million years flexural ridges and troughs develop. (b) Deflection of the vertical peak retains its high initial value reflecting the persistence of the bathymetric scarp. (c) Geoid step changes in shape but not in overall amplitude as the FZ ages (Sandwell, 1984).

above the fracture zone with a negative sidelobe on the older side. An analogous pattern occurs along the right in active fracture zone segment. Thus, along all inactive portions of the Udintsev fracture zone, there is a prominent sidelobe on the older side with a small or absent sidelobe on the younger side.

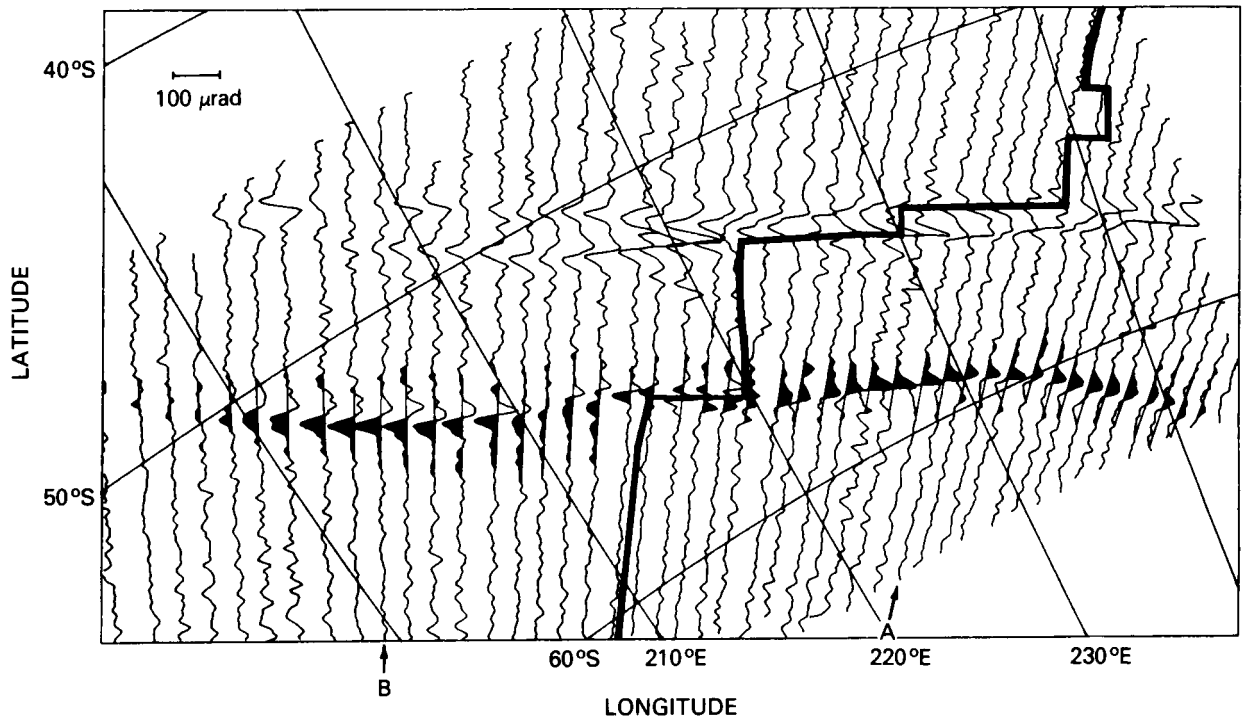


Figure 10. Along-track deflection of the vertical profiles from differentiated Seasat altimeter passes. Map projection is oblique Mercator where pole is the relative rotation axis between the Pacific and Antarctic plates. The plate boundary (heavy line) consists of spreading ridges (vertical lines) and transform faults (horizontal lines). Highlighted peaks reveal the characteristic signature of the major age offset Udintsev FZ.

Measurement Requirements

The primary geophysical objective for the Eos altimetric system is to perform multiyear mapping of the global ocean with 10 cm absolute radial accuracy and with a spatial resolution greater than 5 km on the surface of the Earth. The radar altimeter system should be dual-frequency to allow for corrections of ionospheric refraction, and it should have an instrument precision of better than 2 cm. Ancillary data should be available to provide atmospheric corrections (e.g., wet tropospheric refraction) to the altimeter measurements.

An essentially non-repeating orbit or an orbit with a repeat period in excess of a year can provide a spatial resolution of about 5 km, normal to the ground trace. The sampling rate of the instrument should provide spatial resolutions of 5 to 10 km along the trace, corresponding to a data rate of about one per second for a nominal 800 km orbital altitude. The spatial resolution and sampling rate interval would allow the generation of crossover data (differenced altimeter measurements at the loci of ground trace intercepts), eliminating geoid uncertainties. Crossover data are invaluable for geophysical mapping of various fields (e.g., the Earth's gravity field and its tidal response). With the availability of a laser altimeter and retroranger, simultaneous and co-located measurements can be made to calibrate the

radar altimeter, providing a means for absolute sea surface height measurements. Absolute sea surface heights provide a precise measurement of surface slope. The possible future availability of multibeam altimeters suggests a means for increasing data coverage, enabling near-real time modeling of the ocean surface. To achieve an absolute radial orbit accuracy greater than 10 cm will likely require the joint use of GPS tracking and laser retroranging.

In conclusion, the continuous monitoring and mapping of geophysical features from space are required for geodesy and geodynamics. The envisioned Eos altimetric system will greatly enhance scientific investigations and applications in the areas of geophysics. The combination of a radar altimeter and laser retroranger will provide a complementary data set invaluable to the scientific community.

CRYOSPHERIC SCIENCES

Ice on this planet exists in a wide variety of forms: the seasonal snowcover that appears each winter, the thin sea-ice cover on the polar oceans, and the more permanent mountain glaciers and vast polar ice sheets. Each of these kinds of ice has an impact on the habitability of Earth. Ice sheets both modulate and respond to global climate. These fluctuations in extent and volume have ranged from no

global ice to twice as much as is present today (Denton and Hughes, 1981). Variations in sea level of up to 70 m from the present level and modified oceanic circulation and composition of the oceans result from such changes in ice volume. Sea ice acts like a cap on the ocean, preventing the exchange of heat between the ocean and the lower layers of the atmosphere. Because the temperature difference between ocean and atmosphere near the poles can be large, the potential heat exchange can be large. Thus the amount of open water within the pack can contribute to a significant amount of heat exchange. Seasonal snowcover is important both for its high albedo, which reduces the absorbed solar radiation, cooling the planet, and for the reservoir of water that is released to the hydrologic basins as it melts during the spring and summer thaw.

The ice sheets respond to climate change with time constants ranging from a century to millenia (Paterson, 1981). This suggests that the present behavior of the ice sheets is a complex response to past climatic conditions with different regions of a single ice sheet responding quite differently to the same climatic history. Thus it is not meaningful to measure the changes of an ice sheet in a limited region and extrapolate the result to the entire ice mass; a total measurement is required. No complete, systematic measurements have been made of either Greenland or Antarctica, yet their combined mass (33 million km³) accounts for 99 percent of the world's ice mass (Drewry, 1983). The net accumulation over these ice sheets lowers sea level an average of about 6 mm every year. Much, and perhaps even more, of this amount is returned to the seas as meltwater runoff and icebergs. The net balance between mass gain and mass loss is not known to better than ± 50 percent. The accuracy of ice sheet net mass balance must be improved to assess its contribution to changing sea level (currently rising at a rate of 1.5 mm per year), and more importantly, global climate.

Ice flows in response to its own weight. How it flows depends on internal rheologic behavior as well as external conditions. Accumulation, ablation, and temperature at the surface as well as heat flow, roughness, and water flow at the bed affect the rate of deformation and flow. The relationship of some of these parameters to ice flow is reasonably well understood but there are numerous gaps in our understanding. For example, the processes controlling the flow of ice streams, the fast moving portions of ice sheets, remain a mystery. Progress from field studies is continuing to shed light on these processes, and the more that is learned the better able we will be to construct models that will project current trends into the future. However, it has become clear that such surface observations will forever be limited in their spatial coverage. These studies must be augmented with measurements on broader scales with satellite remote-sensing instrumentation.

Because ice sheets are composed of accumulated

snow over many years, their cross section is a stratigraphic history of past climatic conditions. Ice cores taken from ice sheets have provided a valuable paleoclimatic record of atmospheric composition. Dating the core profile, however, is a difficult problem because the deeper ice originated upflow from the core site. Thus, understanding ice dynamics again becomes a necessary step in allowing scientists to glean the maximum amount of information from ice cores.

A basic question addressed in sea ice studies is the interaction of the sea ice with the ocean, the atmosphere, and other sea ice. There are both thermal and dynamic interactions. One thermal interaction is the large difference in absorbed radiation between the bright sea ice (especially with a snow cover) and the dark ocean due to the difference in albedo of these two surfaces. Another interaction is the heat conducted into the sea ice from the warm ocean and the heat removed from the ice by a cold (winter) atmosphere. The existence of sea ice between the warm ocean and cold atmosphere greatly reduces the amount of atmospheric warming.

The ice pack is composed of an aggregate of individual floes that also interact with each other in areas of convergent motion. These dynamic interactions involve the motion of and deformation within the pack ice in response both to oceanic forcing by currents against the rough ice bottom, and to atmospheric forcing by winds against the rough ice surface. Identifying and predicting where convergent zones occur and where divergent zones are, or will be, is of extreme importance to Arctic shipping and drilling platforms.

Much of the Earth's freshwater resource falls to the surface as snow and is released only as this snow melts. The high albedo of snow is a very effective reflector of incoming solar radiation tending to cool the planet. Also, the distribution of snow thickness is highly non-uniform in space and time. These variations have a significant impact on the rate at which meltwater is released to the hydrologic cycle. The distribution of snow and its mass are of primary concern to the snow hydrologist.

Observational Requirements

Research and operational problems in the cryosphere require the measurement of a variety of snow and ice variables. In this section, we attempt to quantify the fundamental geophysical variables (in terms of accuracy, precision, spatial resolution and sampling interval) required by the research community. In many cases, these requirements are the same for both basic ice research and climatological research.

The ability to meet these requirements will be dependent upon a comprehensive data collection and analysis program, including *in situ* surface observations and a continuing research and development program in advanced altimetry systems. Since several

variables of significance to cryospheric research are derived from multiple instruments, a successful research program will also be dependent upon the data and information system supporting Eos.

Ice Sheets

Mapping the surface elevation of ice sheets is necessary for two reasons. First, when repeated, it provides a measure of volume change. For this, the areal extent of the ice sheet as well as the elevation of the surface need to be measured. Changes in volume or extent translate directly into changes in global sea level. Even a relatively large imbalance, equal to 30 percent of the present average accumulation rate in Antarctica, would only change the surface elevation by an average of 5 cm per year. Thus, the lower the precision of an altimeter, the more time would be required to be certain of a change of this order. A requirement of 10 cm in surface elevation over flat terrain is adequate to detect major volume changes in a decade. This accuracy will degrade somewhat over the sloping portions of the ice sheet (Brenner *et al.*, 1983) but this effect will be compensated for by the effect of larger thickness changes at the margins, which are due to more active ice flow and higher accumulation rates. To adequately map the surface would require the accumulation of a dense network of transects with a minimum spacing of 5 km. A data set of this size would require about 6 months to collect. To look for statistically significant changes in volume, this survey should be repeated every 2 years.

The calving of icebergs from the margins of ice sheets represents most of the ice mass lost from Antarctica. This process tends to be episodic, with large, slow advances of the margin until, after some years, a large iceberg calves, causing a sudden retreat of the margin. Monitoring the marginal ice position to ± 100 m on a routine basis will contribute significantly to measuring the mass balance of Antarctica.

The other important reason for mapping the surface elevation is that the detail of the undulating surface contains information on the character of the ice flow. The direction of flow is along the maximum surface gradient averaged over a distance equal to 20 times the ice thickness. Knowledge of flow directions permits drainage basins to be delineated (Bindschadler, 1983). To measure mean slopes of 0.002 rd over a distance of 30 km to 10 percent accuracy requires elevations to be known to ± 3 m. Surface undulations over a smaller scale (three to five times the ice thickness) are proxy indicators of conditions at the base of the ice sheet. Smooth, horizontal ice indicates the presence of subglacial lakes, whereas a slightly rougher surface but with a low mean slope indicates a well-lubricated and usually fast-moving glacier or ice stream. Still rougher surfaces correspond to slow or thin ice often frozen to the underlying bedrock. The undulations typically have wavelengths of a few tens of kilometers and

amplitudes of a few tens of meters. A large-footprint altimeter is not capable of measuring these undulations because the first return will always be from the surface peaks (Gundestrup *et al.*, 1986). Some information on the surface height distribution will be contained within the returned power after the first arrival, but the deconvolution of this information is very difficult if not impossible for realistic surfaces. Thus, to measure these surface features, a footprint of less than 100 m diameter on a flat surface is required.

If the altimeter is capable of ranging to surface-based retroreflectors, absolute ice motions and deformation can be measured (Degnan, 1981). This capability would open up an entirely new domain of measurement to glaciologists since the time between sequential surveys of the ice sheet elevation can be used to monitor the annual and seasonal motion and deformation of the ice. A laser-based ranging device could provide these measurements. Such a laser ranger could be used for repeated surveys of surface networks of retroreflectors. In central Antarctica velocities are only very few meters per year, but velocities increase by several orders of magnitude toward the coast. The ability to measure absolute positions to a few meters is available now through surface-based geocivers, but the logistic cost of repeated ground-based occupation of field sites is prohibitively high. Monitoring networks of retroreflectors to a position accuracy of 1 m in all three coordinates and 10 cm in relative positions would accelerate the rate at which surface motion data of the ice sheets are being collected and allow surface-based field crews to conduct other studies not yet possible from space.

Sea Ice

Sea-ice topography appears quite different than that of ice sheets. The differential elevation between ice elements is small; the freeboard of first-year ice is only 10 to 20 cm. For multiyear ice it may reach 30 cm, while ridges (formed where individual ice floes have converged) can reach 10 m; but they are typically quite narrow (a few tens of meters). To measure freeboard differences the range precision must be better than ± 5 cm and to distinguish leads at a resolution of 50 m requires a footprint of comparable size.

Measurement of the surface roughness can be accomplished through examination of the return pulse shape. In general, the broader the return pulse shape, the rougher the surface. Rougher ice tends to be older, but this character also depends upon the divergence of the flow field. Roughness should be measured on horizontal scales of 100 m and 50 cm vertically.

Snow

Monitoring the seasonal snowpack over open ground requires frequent measurements to account for densification of the snowpack between

snowstorms. This should be done every few days to an accuracy of ~ 10 cm. In all regions where the snow thickness is to be measured, a baseline profile without snow needs to be measured. Then, when snow is present, repeat measurements need to be made as coincident as possible with these baseline profiles. Errors resulting from non-coincidence will increase with the surface topography variation. If coincidence can be maintained within a few hundred meters these techniques can be useful in all but the more mountainous regions.

Altimetric Systems

Within the cryospheric research community, it has been recognized for some time that a single altimeter could not produce all of the needed measurements and still provide the accuracy and precision required (Campbell, 1979). It was this determination that led to the use of instrument systems concepts during the ICEX planning era. At that time, consideration was given to an altimetric system composed of two complementary subsystems, a radar altimeter and a laser altimeter and retroranger. The radar altimeter provides a continuous profile of the ice, measuring surface topography, surface slope, and to a degree, roughness. The laser altimeter and retroranger performs high-precision altimetry and produces correlative data useful for calibrating the radar altimeter measurements, for resolving ambiguities in these data, and for providing direct measurements for calculating ice sheet flow velocities. We too consider a similar system and recommend its incorporation in Eos planning. In this section, we therefore address the advantages and disadvantages to radar altimeters, laser altimeters, and the combination of both instruments into a single altimetric system.

Radar Altimeters

Radar altimeters have already proven themselves as a useful instrument for ice sheet research. Surface topography has been measured by both the GEOS-3 (Brooks *et al.*, 1978) and Seasat (Zwally *et al.*, 1983) radar altimeters. The Seasat data have also been used to measure the positions of ice shelf edges and ice walls at the margin of Antarctica (Thomas *et al.*, 1983). While these applications have served to illustrate the utility of radar altimeters in cryospheric research, they have also demonstrated their deficiencies.

Elevation accuracies over the flatter, central regions of Greenland approach 1 m, but this accuracy degrades rapidly as surface slope increases (Brenner *et al.*, 1983) until near the edge of Greenland the errors exceed 100 m. Large mean slopes cause a broadened return pulse that was not considered in the design criteria of the Seasat altimeter. The result is a loss of ranging precision and eventually a loss of signal. The Eos altimeter should be designed with more flexibility in the algorithm that acquires and

processes the return pulses (i.e., the tracker algorithms).

Another problem with the radar altimeter measurements over ice sheets is related to their relatively large footprint. Ice sheet topography is sufficiently rough that the return pulse represents a complex integration of transmitted energy reflected from a few scattered high spots within the footprint, followed by energy reflected from surfaces progressively further in range from the altimeter (Martin *et al.*, 1983). It was not known which point along or beside the ground trace first reflects pulses, and there were not enough ground traces to resolve the ambiguities in these data. Nevertheless, what these altimeters have provided is an effective average range to the surface within the footprint. These are still valuable data when searching for elevation changes over an extended region.

An improvement to the radar altimeters that could greatly facilitate the interpretation of the range data is a multibeam altimeter. The addition of multiple ranges either fore-aft or crosstrack provides repetitive measurements of the same area in the former case or additional swaths of data for cross-slope analysis in the latter case. In either case, the added data would help resolve the uncertainty of where the first return energy originates.

Laser Altimeters

While it is unlikely that the broad beam of radar altimeters would ever prove highly useful for research on sea ice or snow, a laser altimeter might afford new avenues for glaciological research (Zwally *et al.*, 1981). Laser altimeters would provide a more accurate single range resolution (a few centimeters) and a much narrower footprint (100 m diameter is possible); although, they impose tighter attitude control requirements. These characteristics would make it possible to measure the roughness of sea ice, occurrence of large leads, and perhaps even snowpack thickness from space. Laser altimeters might also permit the direct measurement of ice sheet surface undulations, indicative of ice dynamics and basal conditions. The smaller footprint would also ensure that the first return energy originates more closely from subsatellite nadir, rather than being displaced laterally in some undetermined direction. This would greatly simplify the generation of accurate maps of surface elevation from satellite altimetry data.

A concern with laser altimeters is the limited lifetimes of the flashtubes. The design of a laser altimeter with the capability of 5×10^7 shots appears feasible with current technology (Bufton *et al.*, 1981). This should provide sufficient sampling to complete a survey of the major ice sheets and possibly a limited follow-up survey. Future technologic innovations may increase flashtube lifetimes and multiple flashtube designs would increase the capacity of a laser altimeter, as well.

Combined Altimeters

Together, spaceborne radar altimeters and laser altimeters serve extremely complementary functions. Deconvolution of the radar return pulse is greatly simplified by a laser altimeter measurement of this same area, providing adequate attitude control is available. If both are aimed together at the same target, the comparison will reveal whether or not the radar first return is from the same area as the narrower laser footprint. Any difference is a direct measurement of surface slope and becomes very valuable in the data reduction of the surface topography. Further, the laser profile will give the topographic relief within single radar footprints and make more feasible the extraction of information contained within the overall shape of the radar return waveforms. Radar altimeters, on the other hand, overcome the short lifetimes of lasers, thereby providing a means of interpolating between the sparse point-measurements of laser instruments.

In conclusion, the sheer geographic extent of ice sheet, sea ice, and snow research requires monitoring and measurement from space. Most of the fundamental scientific issues in glaciology can be addressed by satellite altimetry. While radar altimeters are limited in their capabilities over sea ice and snow, their utility has already been proven over ice sheets. A multibeam radar altimeter might further extend these capabilities, supporting much-needed glaciological research. The higher precision and smaller footprint of laser altimeters are features that permit a wide range of applications to ice sheet, sea ice, and snow research. A pointable laser ranger would enable even more critical research—which otherwise must be carried out by ground-based surveys—to be conducted from space. Finally, the combination of both radar and laser altimeters would provide a data set that may be far more useful than either instrument alone.

GEOLOGY

Studies of the solid Earth, for both geological and geophysical investigations, rely heavily on the availability of high-resolution, high-precision topographic data. The topographic expression of geologic structures is fundamentally related to their origin and subsequent erosional history. Topography thus reflects not only the character of the tectonic and erosional environment within which a given landform has evolved, but also provides information on crustal structure (rheology, thermal gradient, and flexural rigidity) and can thus serve as an important boundary condition in mechanical models of regional- to continental-scale geological problems.

High-resolution topographic data from the Eos altimeter is therefore seen as serving many diverse needs for the geological community. Indeed, almost all of the disciplines concerned with the solid Earth

(e.g., geophysics, geomorphology, geobotany, hydrology) would directly benefit from an improvement in the regional- to global-scale topographic data base at a spatial scale commensurate with the other data bases such as imaging spectrometers (High-Resolution Imaging Spectrometer (HIRIS), Landsat Thematic Mapper) and imaging radars (Eos SAR, Earth Resources Satellite (ERS-1), Japanese Earth Remote Sensing Satellite (JERS-1)) available from Eos and free-flying satellites. Investigations of the regional tectonic processes associated with mountain building, quantitative analysis of landforms to infer both present and past surface processes, and the geometric correction of multispectral satellite images (such as Landsat Thematic Mapper scenes) all require topographic data of the kind that would be derived by the Eos altimeter.

To date, only small-scale (10 m to 1 km in linear dimension) geologic and geomorphic features have been topographically characterized on an extremely local scale; the highest spatial resolution topographic information at a regional scale is a 1 km resolution data set covering the United States produced by the U.S. Geological Survey from digitized topographic maps. For many parts of the world, but particularly in Asia, South America, and Antarctica, relative topography is known only to several hundred meters at a spatial resolution of about 10 km. A strong need therefore exists to extend high spatial and vertical resolution topographic data bases to the continental scale in order to perform long-wavelength (1,000 to 10,000 km) geophysical studies, and to intercompare the absolute elevations of one continent with another; the Eos altimeter can fill this crucial role, by constructing a global land topographic data set over a period of several years from a series of orbital ground tracks.

Geologic Applications

Following recommendations made by the National Research Council, personnel within the NASA Geology Program have identified several research areas of special interest which would benefit greatly from the complementary information provided by Eos altimetry. One topic centers on the interpretation of regional-scale tectonic processes associated with mountain building and continental evolution. For example, the manner in which the Andes and Himalaya mountain belts have been created due to plate tectonic processes, and the geological evidence for the occurrence of plate tectonic processes during former periods of the Earth's history (dating back as far as the early Archean more than 2.5 billion years ago), can both be addressed with high spatial and vertical resolution topographic data. In many parts of the world, basic information on regional topography is lacking both for mapping purposes and for correlation with other orbital data such as gravity and magnetics. For example, topographic information on

the long-wavelength (100 to 10,000 km) signatures of mountain belts and the stable continental shields would significantly improve the geologist's ability to construct gravity models of these areas, and hence infer lithospheric processes responsible for their formation.

Not only is the land area of the Earth an important area of study using the Eos altimetric data, but also the tectonic and volcanic processes operating on the ocean floor can also be investigated indirectly using topographic variations in the ocean surface (Haxby *et al.*, 1983). Measurements made by the altimeter on the Seasat spacecraft have provided fine examples of how the seafloor topography (Dixon and Parke, 1983) and gravity field (Freedman and Parsons, 1986) can be derived from altimetry data over the oceans. These gravity data can be used not only to identify previously unrecognized seamounts on the ocean floor, but also to calculate crustal thicknesses for the ocean basins based on the degree of compensation of these seamounts. Structural and volcanological interpretations of spreading centers and convergent plate margins on the ocean floor therefore provide many of the important missing links in our attempt to understand the global tectonic processes that are inadequately represented on the continents.

A second major focus within NASA's Geology Program is one that utilizes the geologic record to infer changes in the Earth's climate from the preserved morphology and distribution of landforms. In this instance, Eos altimetry data could provide crucial information on such phenomena as paleo-lake levels (hence, decade to million-year variations in rainfall), changes in the regional gradients of river systems (due to climate induced variations in river discharge, or due to tectonic uplift), and volumes of volcanic material erupted from volcanic centers. In quantitative geomorphology, landform interpretation has focused on the spectral analysis of one-dimensional topographic profiles across a variety of different features in an effort to identify dominant wavelengths associated with surface and crustal processes (Pike and Rozema, 1975; Morisawa, 1985). The objective of such studies is to identify characteristic topographic signatures of pristine landforms (e.g., river deltas, volcanic lava fields, desert sand dunes) and landforms that have been modified by weathering and tectonism (e.g., slope development within drainage basins, and the production and transportation of rock debris in mountain belts found in different climatic environments). Thus, well understood geomorphic landforms and associated processes can be inter-compared with geographically more isolated examples in order to identify trends in landform distribution associated with temporal changes in climate and the age of surface materials.

Currently, these quantitative geomorphic studies are by the nature of the original topographic data base limited in geographic extent, concentrating on features of a few kilometers in horizontal extent and

at a vertical resolution of a few to 100 m. Thus a global Eos-derived altimetry data set would permit, for the first time, a variety of geomorphic analyses to be conducted. Examples of several different landforms that would be of interest to the geomorphologist, and the spatial and vertical resolution of an altimeter that would be required to study these features, are given in Figure 11.

Observational Requirements

Not only would altimetric data derived from Eos significantly increase the geologist's capability to perform higher-order spectral analyses of landforms due to improvements in vertical accuracy, but also the acquisition of two-dimensional data sets (built up from adjacent Eos orbital ground tracks over a period of days to years) over large horizontal distances would enable these studies to be extended to global scales. Erosional histories of different continental shields, their isostatic recovery following deglaciations, and the global nature of sea-level changes could all be investigated whether the spatial resolution of the altimeter were 30 m or 1 km. Key attributes of the topographic data set would be the horizontal integrity (i.e., the data would have to be referenced to the same datum on a global scale) and the two-dimensional completeness of the data set. Cross-track measurements of landforms will frequently be required, and so no "data gaps" perpendicular to the Eos flight-line could be tolerated, whether the spatial resolution of the altimeter were a few kilometers or a few tens of meters.

An issue that is even more important than the two-dimensional integrity of the altimetry data set is the ability to obtain topographic data at a spatial scale that is comparable to other Eos instruments. Such an ability will be valuable for the removal of slope effects from both imaging spectrometer (HIRIS) and radar (SAR) images. Both of these other instruments are expected to have a spatial resolution of approximately 30 m. In many instances, quantitative studies of spectral properties will require that local viewing geometries at the pixel scale will have to be removed before the albedo, particle size, or surface roughness effects can be removed from the spectra. Such studies might include the interpretation of vegetation stress from HIRIS data of vegetated hillslopes, the local aspect of surfaces when thermal models for their emissivity and thermal inertia are being developed, or the effect of local slopes on radar backscatter data when the radar cross section area is being calculated. In addition, because stereo-radar may provide more closely-spaced cross track topographic information than an altimeter (Leberl *et al.*, 1986), the ability to inter-leave limited areal coverage stereo SAR data with long baseline altimetric data will provide both local and regional context for an area (Watts and Daly, 1984). Thus the ability to co-register Eos altimetry and HIRIS or SAR data at the same spatial

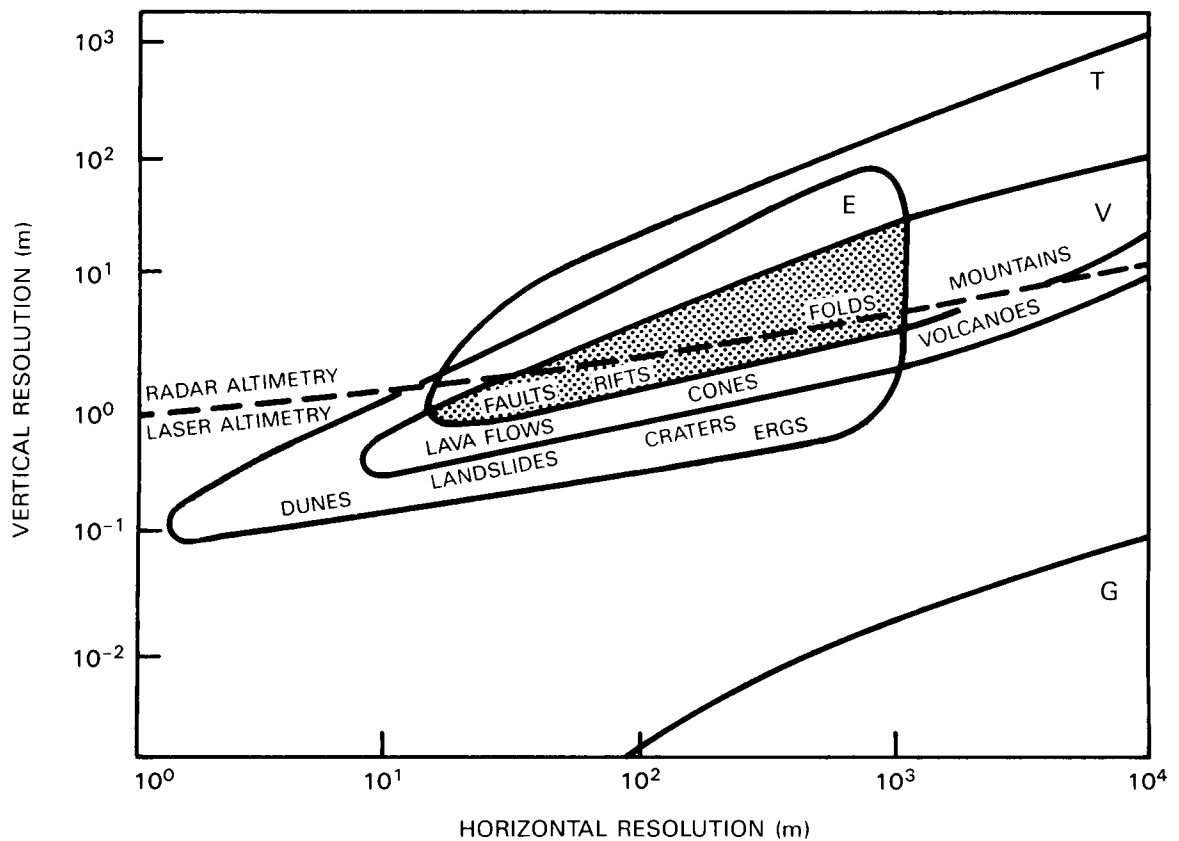


Figure 11. Topographic feature resolution envelopes for general landform types and geodynamic processes (G). Landform classes are subdivided as indicated, and the stippled region represents the zone of intersection of the three basic classes of volcanic (V), erosional (E), and tectonic landforms (T). The approximate lower resolution of currently available radar altimeters adjusted for operation over land is shown by the dashed line. Note that existing laser altimeters (operating in profile mode) easily exceed the vertical resolution limitations of radar altimetry and in many instances, due to their higher spatial and vertical resolution, laser altimeters are required to adequately investigate these landforms. (Diagram from J.B. Garvin, Goddard Space Flight Center, unpublished data).

resolution (30 m) is therefore highly desirable, since only in this manner can local topographic gradients be uniquely separated from physical property effects. This ability to merge multispectral and digital topographic data bases at the same scale will also be of great value when topographic studies are combined with lithologic mapping using orbital data sets in order to infer the three-dimensional geologic structure of a region (cf., Conel *et al.*, 1985).

Vertical accuracy of an altimeter over land is a system requirement for which little information is currently available from the geologic community. While certain very flat targets such as river flood plains might be measured to a precision of a few tens of centimeters, the height estimates over mountainous terrain would most likely be biased toward the topographic highs at the pixel scale, from which the first returns would be obtained. In such situations, the regional slope of the surface will most likely prove more valuable, but the minimization of this "elevation averaging" over rugged terrain is an additional justifi-

cation for the highest spatial resolution that can be obtained from the Eos altimeter.

As with the measurement of sea ice (see above), the ability to determine surface roughness of geological targets is of value for lithologic discrimination and for comparison with radar backscatter values from the Eos SAR. The ability to examine the return pulse shape from the altimeter is therefore an additional system requirement for the Eos altimeter. It is believed that, together with the requirement for 30 m spatial resolution, the preservation of the signal pulse shape would favor a laser altimeter for land measurements from Eos.

Repetitive coverage of land areas is also a key aspect of geological studies using the Eos altimeter. Although much of the land surface of the Earth does not vary in altitude at a rate that will significantly change during the lifetime of the altimeter, some geologic processes do alter the landscape at the appropriate rate. For example, lake levels and alpine glacier volumes are both likely to change on a period

of months to years. Dramatic variations in the shapes of volcanoes such as Mount St. Helens may occur as a consequence of catastrophic explosive eruptions, while pronounced flooding of river deltas and the change in geometry of coastal sand bars may occur in a matter of hours following hurricanes or very heavy rain. In these and other instances, the ability to compare Eos altimeter data obtained before and after the event would provide important first-order information on landform change. The frequency at which these repeat topographic measurements are made is geologic application-specific, but the capability to remeasure the altitude of any point on the Earth's surface within 3 to 5 days would satisfy most investigations of dynamic geologic phenomena.

In conclusion, the following altimetric system requirements would maximize the benefits of the data set for geological purposes:

- The ground trace spacing should be equivalent to the spatial resolution of the altimeter.
- The platform orbits must be determined to an accuracy that will allow absolute elevations to be intercompared between continental land masses.
- The spatial resolution of the altimeter should be equivalent to that of HIRIS and the radar (SAR). Only in this manner will a number of albedo, slope, and surface roughness effects be resolvable with the three instruments working synergistically. For this reason, one component of the Eos altimetric system (the laser altimeter) should have a spatial resolution of 30 m.
- Most geological problems can be adequately addressed with an altimeter that has a vertical accuracy of 10 to 20 cm, although it is recognized that this accuracy will not be easily attained and may not be overly meaningful in areas of topographically rugged terrain, whatever the spatial resolution.
- The altimeter should have the ability to preserve the entire return pulse shape, in order to study surface roughness effects and to correlate this information with radar backscatter measurements obtained by the SAR.
- The Eos altimeter should have the capability to obtain data for any portion of the world within a time period of 3 to 5 days in order to investigate transient (or catastrophic) geological phenomena.

PHYSICAL CLIMATOLOGY

The Earth's physical climate system is driven largely by solar heating that produces geographically different patterns of circulation, precipitation, evap-

oration, vegetation, and hence climate. Central to the physical climate system is the existence and abundance of water in all three phases. Yet, although studied for many years, our knowledge of the distribution of precipitable water is quite poor. This is largely a result of our inability to make accurate and precise measurements of rainfall over the open ocean and inland seas, regions that dominate the Earth's surface area (approximately 78 percent of the total area). Although newly emerging acoustic techniques promise relatively accurate rainfall measurements over the ocean, this instrumentation cannot be deployed in adequate numbers to quantify the global distribution of precipitation.

By combining AMSR rain emission measurements (from the water vapor absorption band at 22.3 GHz) with radar altimeter rain scattering signals (obtained differentially from measurements at the surface and at an altitude of a few kilometers), it should be possible to obtain relatively precise rainfall rates. The precision of the measurement is dependent, in part, upon the relationship between radar scattering and rain rate. Figure 12 depicts this relationship and shows that the backscattered energy is a well behaved function of rain rate. Since rain emission, rain scattering, and rain rate represent different statistical moments of the distrometric distribution of rain, the rainfall distribution (rain rate and areal extent) can be accurately specified when two of the three variables are known. Thus, the synergistic use of both a microwave radiometer and radar altimeter in the Eos payload affords the opportunity to make rather dramatic progress toward quantifying precipitation, a central element in the physical climate system.

This technique has been demonstrated experimentally by Ulbrich and Atlas (1978), who achieved accuracies of about 10 percent. We expect that the inherent difficulties of making these measurements from spacecraft altitudes will degrade these accuracies somewhat. However, significant improvements (i.e., much lower noise levels) in both the radar altimeter and microwave radiometer continue and will likely have an offsetting effect.

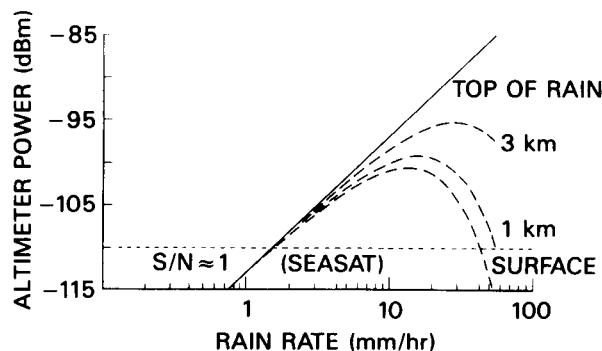


Figure 12. Altimeter power backscattered from rain as a function of rain rate with the height of the scattering region as a parameter.

Requirements for ancillary measurements such as precipitation do not involve the traditional specification of accuracy and precision. Rather, they are confined to frequencies, sampling gate sizes, and tracker flexibility. Since rain rate measurements involve the synergistic use of both a radar altimeter and microwave radiometer, frequency specifications apply to both. For the altimeter, frequencies of 5.3 and 13.6 GHz should be adequate. Appropriate radiometer frequencies should include 37, 22, and 18 GHz. Altimeter sampling gates should be sized to allow the atmospheric column to be subdivided into 500 m bins and the tracker must be sufficiently flexible to allow first returns to be acquired at altitudes (above the Earth's surface) of about 20 km.

Beyond the synergistic use of a radar altimeter and microwave radiometer for rainfall measurements, to provide a consistently accurate and precise global data set, the statistics of rainfall geographic distribution and correlative *in situ* data will be required. Over land surfaces (approximately 22 percent of the global surface area), this information can be acquired by Eos through the global weather network. Over the remaining 78 percent of the Earth's surface, the oceans, these data would be acquired through a carefully designed array of acoustic sensors that would telemeter their data via the ADCLS.

OPERATIONAL NEEDS

There are a host of operational uses for measurements from radar altimetric systems. They range from the determination of the ionospheric free electron content for the communications industry to applied problems of national defense. In this section, we limit our discussion to the requirements of NOAA since their uses are typical of many operational agencies.

The operational functions, hence objectives, of NOAA require that they maintain an observational data base that serves as either a primary tool for the activities of a particular agency or is itself the object of a particular function. Agency responsibilities are thus the basis for establishing the requirements of their needed data base and these, in turn, translate into measurement requirements imposed upon a specific instrument system.

The operational nature of a particular agency (e.g. National Weather Service, National Ocean Service) requires that they provide daily environmental advice and information that has an impact upon the safety and economic well-being of both individual citizens and the United States as a whole. This time-

liness factor is levied upon all requisite satellite systems, including the altimeter, although the temporal sampling interval varies as a function of the specific variable to be measured.

In their document "ENVIROSAT-2000 Report," the integrated requirements of all pertinent NOAA organizations are presented, including the operational communities' sampling envelope for an altimeter deployed during the next decade. Table 2 is extracted from this report.

While these requirements from the operational sector are not entirely different than those of the research community (in terms of accuracy and precision), there are some notable differences. In particular, as operational requirements, the sampling frequencies are faster than a researcher will normally require and well beyond the repeat times envisioned for Eos (Butler *et al.*, 1987). Additionally, while the proposed requirements for the Eos data and information system (Chase *et al.*, 1986) are rather stringent, the delay times between data acquisition and delivery of processed data are beyond what is reasonably achievable in the Tracking Data Relay Satellite System (TDRSS) era. Direct downlinks will augment TDRSS for operational purposes; it is conceivable that any excess capacity in these links could be used to downlink tracking data from GLRS and GPS.

SUMMARY

Given a widely differing set of objectives, it is not surprising that the design measurement requirements for an altimetric system cover a broad spectrum of possibilities. Perhaps the most straightforward means of rationalizing the diversity of requirements lies in selecting the most stringent specification from each category. Thus, Table 3 summarizes requirements based upon various discipline needs and gleans from them a set of design goals that would satisfy the most difficult requirements.

Although it is unlikely that a single radar instrument could meet all of these design goals, the current generation of radars, augmented with laser measurements, could be adapted to meeting the majority. Consequently, we consider an instrument system composed of both radars and laser instruments together with supporting subsystems. We consider radar instruments in the next chapter; details of a laser instrument are contained within the LASA Panel Report (Curran *et al.*, 1986). (We recommend some modifications to the LASA instrument to provide measurements of scientific interest to those disciplines represented by this Panel.)

Table 2. Operational Altimeter Requirements from the National Oceanic and Atmospheric Administration

Variable (unit)	Accuracy	Precision	Range	Resolution	Frequency	Delay	Coverage	Grid
National Weather Service								
Wind stress) (dynes/cm ²)	0.2	—	—	200 km	5 days	—	—	—
Currents (cm/s)	2	—	—	50	1 week	—	—	—
Ice (%)	2	—	—	—	1 month	—	various	—
National Ocean Service								
Winds (m/s)	—	0.5–2	0–100	5–20 km	3–12 hr	1–6 hr	regional	10–100
Topography (cm)	—	2	0–50	10–20	6–12	3–6	global	10–100
Wave height (m)	—	0.5–1	0–50	5–20	3–12	1–6	global	10–100
Tides (cm)	—	5–10	0–1.5 m	1–50	3–12	1–6	global	10–100
Currents (cm/s)	—	5–10%	0–500	5, 10, 50	6–96	3–48	global	10–100
Office of Oceanic and Atmospheric Research								
Winds (m/s)	0.5	0.5	0–75	100	1 week	10 day	global	—
Topography (cm)	1	1	1–30	100	1 week	10 day	global	—
Ice (km)	1	1	—	1	1 day	12 hr	polar	—
Currents (cm/s)	1.5	2.5	0–250	1, 10, 100	3, 6, 24	12	coasts	100
Waves (m)	0.3/10%	0.2, 0.3	0–30	5	3, 6, 24	3, 12	coasts	10–100
Winds (m/s)	0.2, 1, 2	0.5	0–75	5	6, 12	3, 6	coasts	100
Tides (cm)	2.5, 20	1.5	0–1.5 m	0.5, 100	3, 6	3, 24	regions	—
National Marine Fisheries Service								
Winds (m/s)	2	0.5	0–75	50–100	16	3	various	20–200
Waves (m)	0.5	0.5	0–25	25–50	3	3	various	100
Currents (cm/s)	25	—	0–500	25–50	3	3	various	100

Table 3. Summary of Design Requirements for Eos Radar Altimeters (Accuracy and Precision Refer to the Height Measurement)

	Accuracy	Precision	Resolution	Frequency	Grid	Repeat Precision
Oceanography	10 cm	2 cm	5 km	10–20 days	50 km	1 km
Geophysics	10 cm	2 cm	5 km	2 yrs	5 km	n/a
Cryospherics	10 cm	5 cm	100 m	2 yrs	5 km	300 m
Geology	10 cm	5 cm	100 m	5 yrs	n/a	n/a
Physical climatology	n/a	n/a	500 m(v)	2 days	10 km	n/a
Operational	1 cm	1 cm	10 km	3 hrs	10 km	—
Design goals	<10 cm	2 cm	~1 km	*	*	*

*Dependent upon the number of altimetric systems deployed and the orbit in which they are placed.

IV. ADVANCED MICROWAVE ALTIMETERS

In its most basic form, the Eos altimetric system would consist of four components: a microwave altimeter, a laser altimeter, a GPS receiver, and a laser retroranger (spaceborne) or retroreflector. Although this is a diverse set of instrumentation, it consists of elements that are all complementary to one another. The element with the highest level of development is the microwave altimeter. Its generic capabilities were well proven with four previous or current spaceflight missions. However, we anticipated that the TOPEX-class instrument could mark the end of one era in altimeter design and a new generation of radar altimeters of advanced design could be ushered in during the Eos timeframe.

All altimeters to date have been nadir-looking, pulse-limited systems, although to achieve the required spatial resolution, wider swath coverage will be needed. This can be produced by multiple satellites placed in the same orbit at different phases or by designing an altimeter that has multiple beams, each of which is capable of doing precision altimetry. Since the Eos program could utilize up to three polar-orbiting platforms, both approaches are feasible and therefore are explored in this report.

TOPEX-CLASS ALTIMETERS

We have noted the inherent trade-off between temporal sampling interval and spatial resolution for spaceborne instrument systems as well as rather stringent requirements for mapping mesoscale features. With this in mind, we argue that multiple platforms deployed at different phases can be used to provide dense spatial resolution topographic coverage needed to adequately map the oceanic mesoscale (Bernstein *et al.*, 1979). Figure 13 convincingly indicates that four separate spacecraft, in carefully selected orbits, could provide 50 km per 15-day space-time resolution, matching the mesoscale variability that appears to dominate much of the open ocean. Since Eos may utilize up to three polar platforms, it is conceivable that the TOPEX-class altimeter could be gainfully employed by Eos with minimal alteration, TOPEX/Poseidon providing the fourth requisite vehicle. We further argue that since the TOPEX altimeter will be the then-current "production" radar instrument, cost of replication would be significantly less than procuring either an older-generation instrument or developing an entirely new-generation instrument.

We note, however, that the three Eos platforms may not occupy the same orbit. In fact, as currently conceived, the circular, sun-synchronous orbits that are under consideration for the platforms are 824 km (1:30 p.m. ascending equatorial crossing), 542 km (1:30 p.m. ascending equatorial crossing), and 824 km (9:00 a.m. descending equatorial crossing). An

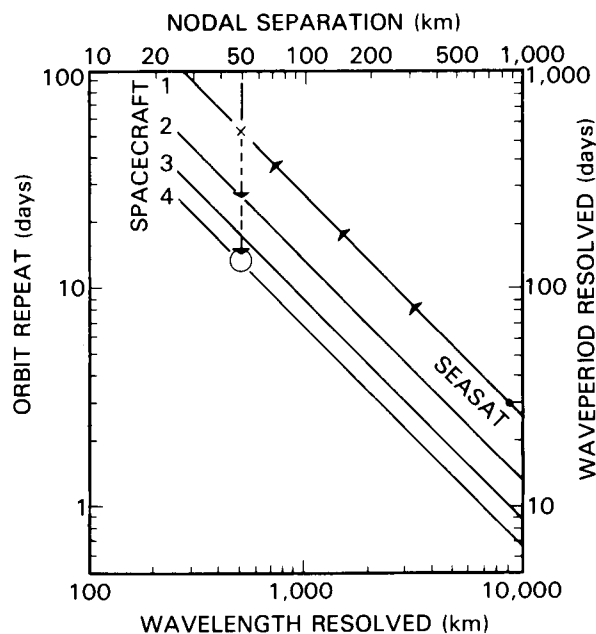


Figure 13. Graphical portrayal of the trade-off between spatial and temporal resolution as a function of orbital nodal separation and repetition period. The example plotted for a nominal 800 km orbit (Seasat) indicates that a total of four separate altimetric systems are required to adequately resolve the oceanic mesoscale (from Bernstein, 1979).

alternate, and by far preferable configuration has all the three platforms at 824 km altitude in circular, sun-synchronous orbits (1:30 p.m. equatorial crossings for two platforms and 9:30 a.m. equatorial crossing for the third). This latter scenario would be superior for the deployment of TOPEX-class altimeters.

In either case, an altimeter system consisting (in part) of three separate radars, each deployed on separate spacecraft of differing orbital characteristics, will present several technical challenges. These include post-acquisition data processing and joint-solution, precision orbit determination of all three platforms. Extensive onboard processing schemes can for the most part be ruled out with this type of configuration, the brunt of the processing task being shifted to the ground (since it would be necessary to have extremely accurate orbits of each of the platforms before the data could be merged and used for scientific investigations).

The TOPEX-class altimeter may be the last of its generation. With its high PRF, onboard ionospheric correction, and highly accurate orbit determination process, the nadir-looking instrument's performance will have reached a level of diminishing returns. However, reductions in size and power are

still possible due to advances in technology. Some considerations for modifications include:

- Increased signal to noise ratio
- Narrower pulse width
- Improved tracking over land and ice

Given its technical maturity and level of sophistication, this argues in favor of multiple platforms each employing TOPEX-class altimeters and providing requisite measurements of the mesoscale field. Another alternative, however, is to develop a new generation of altimeters: multibeam altimeters.

MULTIBEAM ALTIMETERS

In addition to deploying multiple altimeters on separate platforms, spatial resolution can be increased by deploying a new class of advanced altimeters that utilize multiple beams, each capable of accurately measuring the distance from the platform to a point on the Earth's surface. Figure 14 shows schematically the geometry of a multibeam altimeter. In this figure, a "pushbroom" configuration is shown, which has off-nadir beams aligned in the crosstrack direction. The individual beam's footprints should be spaced in the horizontal plane to achieve the swath widths needed for various scientific applications. The extent

of the footprints is determined by the beam-forming antenna system on the platform. It is important to note that the addition of off-nadir beams does create a significant increase in the number of crossing points generated by the intersection of ascending and descending orbital ground traces. These crossing points have proven very important in satellite altimetry because the geoid is a constant at a given location, thus permitting its ready removal from the data. Assuming then that surface dynamics can be neglected or independently corrected, the crossing points can be used to identify and hence correct for orbital uncertainties and attitude uncertainties.

Figure 15 shows the variation in boresight range from nadir for off-nadir angles of 0 to 5°. If a swath width of 100 km is desired, then a 50 km spacing on one side of nadir can be achieved from an altitude of 800 km with an off-nadir incidence angle of 3.57°. From 500 km, the angle must be increased to 5.71°. The scattering of electromagnetic radiation by random ocean surface waves changes dramatically with the viewing incidence angle. Consequently, the angle of the outermost off-nadir beam should be as small as possible to minimize the scattering variability across the swath width. This argues for a higher orbit for a multibeam altimeter.

The ramifications of off-nadir geometry on precision elevation measurements are depicted in Figure 16. In contrast to the nadir situation where the time

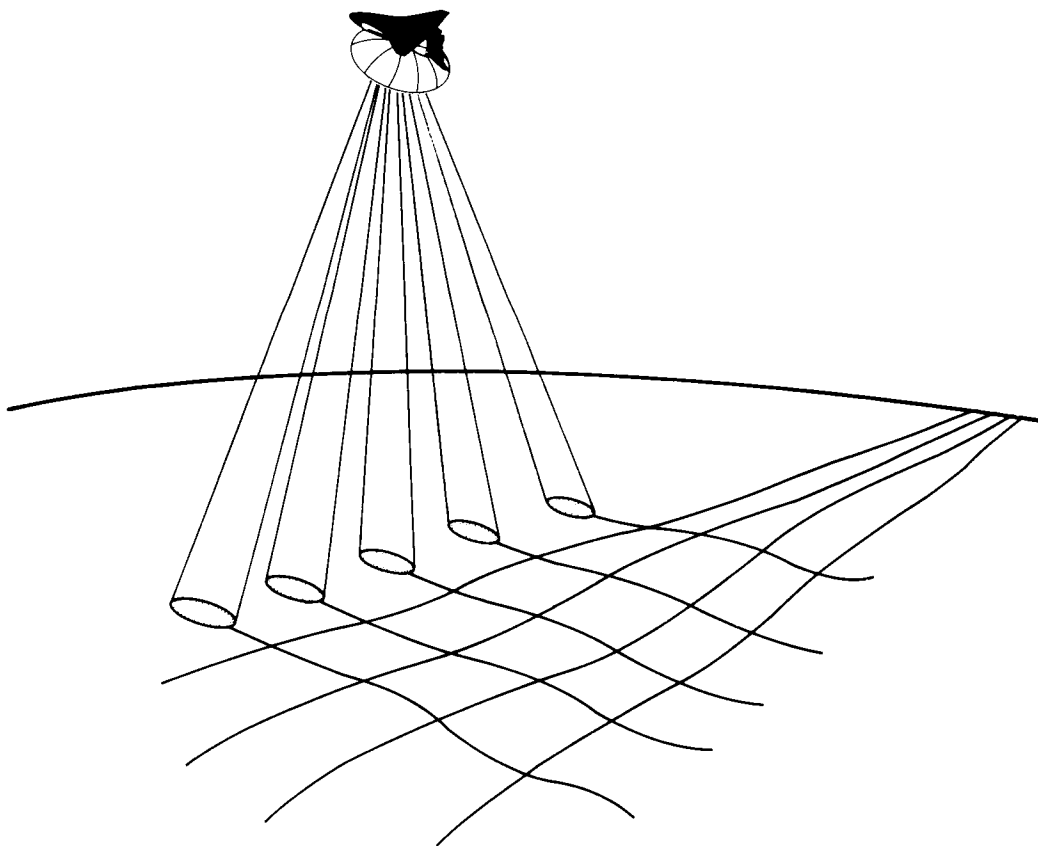


Figure 14. Schematic geometry for pushbroom multibeam altimeter.

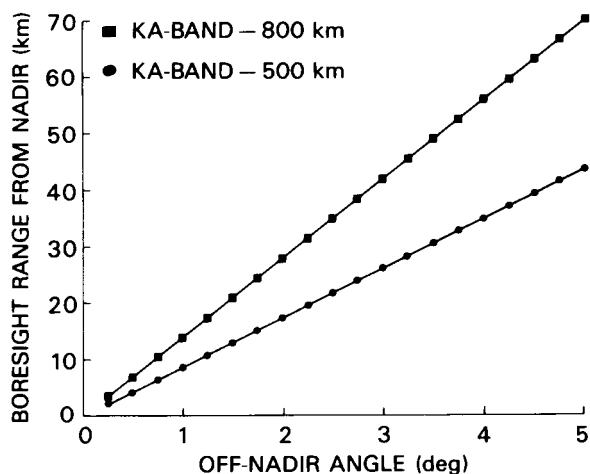


Figure 15. Range variation as a function of off-nadir bore-sight attitude angles.

duration of the footprint's illumination is essentially one pulse width long, the off-nadir footprint's illumination period lasts for many pulse arrivals. To do high-precision range tracking, a sharp backscattered pulse waveform is needed. Figure 16 shows that this is not possible for a conventional, pulse-limited altimeter because of the smeared waveform resulting from the viewing geometry. Narrowing the width of the backscattered waveform, or alternatively decreasing the footprint's size, reduces waveform smearing and can be achieved by using a beam-limited, rather than a pulse-limited, altimeter. A beam-limited system of this class would be needed for Eos if only one altimeter were deployed on one of the platforms.

INSTRUMENT DEFINITION

In this report, this baseline system is founded upon a TOPEX-class altimeter. This instrument is designed to maximize the tracking precision over the ocean. For the combined K_u - and C-band channels this precision should be less than 2.3 cm at a significant wave height (SWH) of 2 m, less than 2.5 cm at a SWH of 4 m, and less than 3.0 cm at 8 m SWH. While the tracker is optimized to produce these precisions, this optimization makes the system more prone to loss of lock if the roughness of the Earth surface deviates significantly from the virtually uniform, random roughness of the ocean. We consider here several enhancements to improve the instrument's performance when used to measure land and ice topography and to measure some characteristics of atmospheric rainfall.

Ice and Land Mode

A significant step toward the solution of the land and ice tracking problem is being taken by the European Space Agency (ESA) with the ERS-1 radar al-

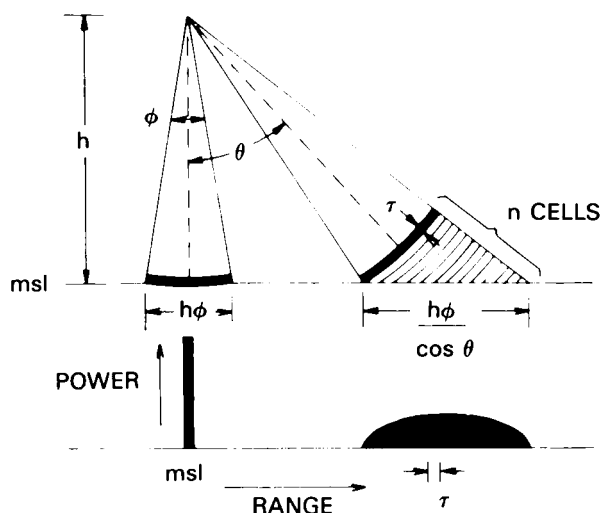


Figure 16. Surface elevation errors as a function of off-nadir attitude angles.

timeter. This altimeter will incorporate two tracking modes with automatic switching in between (Wingham, 1986). The switching algorithm capable of achieving this must be reliable with switching occurring when needed but with a low false-alarm rate. It must determine which tracking algorithm should be used to control the position of the range window and the instrument gain, and it must determine which of two range resolutions should be used to sample the return waveform. The standard oceanographic altimeter tracking algorithm attempts to position a waveform sampling window such that the location of the half-power point of the fast-rising leading edge of the ocean return remains constant. For quickly varying terrain profiles such as those encountered over land and ice, this alpha-beta tracker is obviously inadequate. The ERS-1 altimeter's second tracking mode therefore is based on a center of gravity algorithm. The first step is to estimate the shape of the return and determine if it is sufficiently ocean-like for the alpha-beta tracker to be used. If not, then the center of gravity algorithm provides a height error for the particular waveform shape to close the range loop. For the ERS-1 altimeter, the range window expands by a factor of four to improve its performance over rough terrain, whether land or ice.

Other features that will be valuable for non-ocean applications include the capability of varying the PRF. Over the ocean, Walsh (1982) has shown that the minimum decorrelation time is set by the pulse-limited footprint, where the Doppler spectrum of the return is narrowest. For higher sea states, the pulse-limited footprint diameter increases and the decorrelation time will decrease. Then the PRF may be increased to reduce the noise on the altimeter height measurement. TOPEX/Poseidon incorporates a variable PRF to take advantage of this ability. For sloping and rough land or ice surfaces, the Doppler spectra

will be broader and also asymmetrical resulting in even more rapid decorrelation. Thus, the Eos altimeter should have a variable PRF and a maximum in excess of the TOPEX rate of 4,000.

The altimeter enhancements needed to transform a TOPEX-class altimeter into an instrument that can perform land and ice tracking without loss of lock in addition to the high-precision oceanographic height measurements can be summarized as follows:

- Multiple track modes are needed so that the complex backscattered waveform shapes and the rapid rate of change of range from waveform to waveform do not cause a loss of lock in the tracking loops.
- Adaptive control of the widths of the sampling gates (that constitute the range window) will be required to accommodate high-relief terrain of land and ice surfaces.
- The PRF should be variable to maximize the noise reduction that is achieved with increasing the number of decorrelated sampled waveforms.

All of these features add complexity to the TOPEX-class altimeter design. To incorporate them into the Eos system design will require adaptive algorithms that are robust and foolproof. A large number of operating modes will tend to complicate the reduction of data, and trackers that oscillate between operating modes are to be avoided. It does not appear that substantial modifications are needed to the existing TOPEX-class hardware design to pursue the land and ice applications. Most of the needed developments are in the onboard processing algorithms.

Precipitation Mode

There have been a number of studies conducted to consider the feasibility of measuring certain precipitation parameters with a spaceborne radar system. The need for this capability is strong; the importance of a global rainfall measurement program has led to a proposal for a Tropical Rainfall Explorer Mission (TREM). This program proposes to fly a spacecraft that includes a two-frequency radar set operating at 16 and 35 GHz. With a 2 m diameter antenna, a 3 km footprint, and a vertical range resolution of 200 m, this system would measure the variation in rainfall rate from the surface to 10 km with a sensitivity of 1 mm per hour.

A previous design by Goldhirsh and Walsh (1982) specifically proposed to modify the TOPEX altimeter design to enable the measurement of path-averaged attenuation, assuming that the underlying ocean surface backscattering cross section is invariant over the spatial scale of measurement or that its variation is known. Also, the top of the rain could be determined by this approach; together with the path

attenuation, this information can be used to deduce an effective attenuation coefficient from which the path-averaged rainfall rate may be extracted. Rather than a redesign, as would be required by the TREM proposal, the Goldhirsh-Walsh approach requires only a minimum of modification to the TOPEX hardware. The normal altimeter measurement is initiated with the transmission of a 102.4 μ s chirped pulse (whose effective width is 3.125 ns) at a nominal PRF of 1 kHz for each frequency. Following this pair of pulses, an uncompressed continuous wave (cw) pulse of the same duration could be transmitted, and the return power from the leading edge may be found using a threshold detection scheme whose level is set near the receiver noise. The reduced rate of power increase as the pulse penetrates deeper into the precipitation layer and is due to the increased attenuation of the backscattered rain signal. A sudden jump in the power level occurs when the pulse reaches the ocean's surface.

The wide variety of rainfall rate measurement techniques that are under study is reviewed by Atlas *et al.* (1982). Numerous modifications of the TOPEX-class altimeter design to achieve a rainfall measurement capability are possible. As a minimum, the Eos altimeter should have the capability of measuring the path attenuation and rain cell top as described above.

SYSTEM INTERFACES

In terms of the Eos spacecraft and the altimeter system, there are several areas where the two must interface effectively to ensure scientific and technical success. Below we list several of the more obvious interfaces between the two, and provide recommendations on how these interfaces could be handled most effectively.

Attitude Control

From a technical viewpoint, the co-location of the Eos radar altimeter with a laser altimeter is both appropriate and beneficial. The Geodynamic Laser Ranging System (also referred to as the LASA-R system) described in Chapter IV of the LASA Panel Report (Curran *et al.*, 1986), has two stated measurement roles. In addition to nadir altimetry, the laser will be capable of ranging at prescribed directions toward retroreflectors located on the Earth's surface. This pointing capability requires spacecraft attitude control that is capable of absolute angular accuracy to within a few arcseconds. A similar degree of angular acuity for pitch and roll of the Eos platform is needed for a multibeam radar altimeter. In Figure 17, the variation of range to mean sea level at the antenna boresight as a function of roll angle for an 800 km altitude and a 50 km off-nadir beam displacement is depicted. An undetected or uncorrected roll

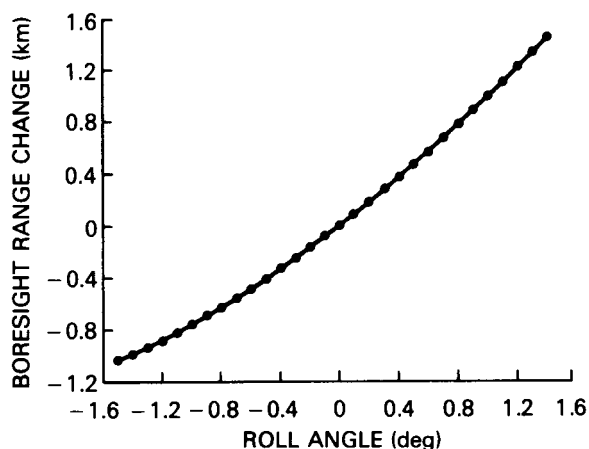


Figure 17. Range variations as a function of roll angle.

angle of 0.1° yields a 90 m range error. Accuracies on the order of an arcsecond, however, result in roll-angle induced range errors of the order of 10 cm. Therefore, there is good reason to deploy both systems on the same platform purely from technical considerations since a specially designed attitude control system would not be needed solely for the radar altimeter.

Data Systems

The simultaneous measurement of high-precision elevation information over a finite swath width has not been accomplished to date. Many advantages can be derived from the additional information, although a concomitant increase in data processing will

be required. Ground-based systems can be utilized for much of the final geophysical data processing, but consideration should be given to onboard processing of both the return pulse waveforms and the initial GPS receiver data. These two data streams could then be merged onboard into a single packet with a single delivery address. We note that the Eos operations center will also require the ephemerides data from GPS and recommend that this data also be replicated in the operations telemetry stream. Additionally, we expect the use of onboard systems for command and control of the altimetric system since we envision that this system will be equipped with a microprocessor, similar to the TOPEX configuration.

INSTRUMENT ERROR BUDGET

The accuracy of the overall height measurement is subject to many error sources, including geoid uncertainties (ranging from about a half meter in well studied areas to about 10 m in remote locations), orbital inaccuracies (which for existing satellites may be as large as a half meter), uncorrected geophysical effects (tides, surface waves, atmospheric pressure, atmospheric water vapor content, and ionospheric free electron content), and instrument specific errors (including time tag, tracker bias, and instrument or electromagnetic bias). These errors and their corrections are summarized in the Appendix. Based upon a preliminary analysis of the altimetric system and platform, we believe that the uncertainty of overall radar height measurements can be held to approximately 8 cm (rss), well within the design goal of 10 cm.

V. OPERATIONAL CONSIDERATIONS

There are several operational factors that affect the utility and scientific returns that will be achieved by an Eos altimetric system. Among others, these include data storage/transmission, calibration, orbit determination, and verification/validation. To place our considerations of these factors in perspective, we make a few assumptions concerning the altimetric system's operational scenario. First, the Eos altimeter will be in continuous operation accumulating data over land, sea, and ice. Data will be transmitted to White Sands, New Mexico, via the Tracking Data Relay Satellite (TDRS). From here the data will be transmitted to the Goddard Space Flight Center and then to the Eos data processing facility. Second, altimeter commands will be generated at the payload operations center, which could be located at a central project control facility or at the principle investigator's home institution. Either of these concepts will be feasible in the mid-1990s given the extensive communications networks anticipated. Third, the altimeter will operate on a 100 percent duty cycle and will contain an adaptive tracker. The adaptive tracker will automatically adjust the onboard tracking algorithm to maintain lock on any surface (ice, ocean, land). Consequently, there should be a minimum of ground-based command and control activities associated with operations of the altimeter.

INSTRUMENT OPERATIONS

Based upon anticipated data generation rates, the altimetric system will require data store and forward capabilities. Two data recording devices will be required; one can be recording real-time data while the other recorder is relaying data to the ground via TDRSS. These devices must be sized to accommodate a continuous operational data rate of approximately 10 to 30 kbps depending on the number of altimeter beams and the amount of data processing occurring onboard the spacecraft. The radar altimeter also will have a calibration and diagnostic mode (waveform burst mode) for transmitting data at higher frequency. This operational mode will increase the maximum data rate by approximately 50 percent. Data from the calibration and diagnostic mode is used in the verification process described later in this chapter.

Data from the GPS receiver and select data from the GLRS onboard the Eos spacecraft must also be transmitted to the regional facility in charge of producing precise ephemerides for the Eos spacecraft. These data could be merged into a single packet onboard, prior to downlink on TDRSS (depending upon the destination addresses of the data). Details of Precision Orbit Determination (POD) for Eos are discussed in the following section.

PRECISION ORBIT DETERMINATION

Satellite-based radar altimeter measurements are generally designed to determine the shape or topography of oceanic features, ice-sheet masses, or land surfaces. In essence, the measurement is a range determination of the height of the satellite altimeter above the subsatellite point at the time of the observation. This range depends both on the orbital height of the satellite and on the elevation of the surface being measured. Therefore, in order to accurately determine the surface topography, it is necessary to know both the height and along-track position of the satellite. It follows that accurate orbit determination is an essential feature of high-accuracy satellite altimetry.

As a result of spacecraft projects such as Geosat and TOPEX/Poseidon we expect that during the Eos era, eddy-resolving ocean circulation models will become operational. These models will use both *in situ* and satellite data in the form of wind fields, sea surface temperature, and high-precision surface topography. We anticipate that these models will be able to advantageously utilize topographic gradients associated with the oceanic mesoscale. These gradients range from a high of approximately 1×10^{-5} (1.0 m to 1.5 m per 100 km) over a western boundary current (e.g., Gulf Stream) to a low of order 1×10^{-7} (1 cm per 100 km) over an eastern boundary current (e.g., California Current), small-scale eddy, or front. On a basin-scale, typical gradients are roughly 4×10^{-8} (40 cm per 10,000 km). These scales set requirements not only upon the accuracy of the instrument itself but also upon the overall measurement system and in particular upon the accuracy with which platforms' orbits are estimated.

Since one goal of Eos is to perpetuate the high-quality data set expected from TOPEX/Poseidon, we assume sea surface topography accuracy requirements for Eos altimetric data are comparable to those for TOPEX/Poseidon (cf. Wunsch, 1981). The radial orbit accuracy requirements for Eos will therefore be of order 10 cm. To achieve operational, precision orbits to this level of accuracy, we believe multiple orbit determination techniques will be needed.

Many factors determine how accurately the orbit of a satellite can be determined. Of these, the two most important are the precision of the measurements of the satellite's position (and/or velocity) and the accuracy of the models used to describe the forces (principally gravity) that influence the satellite's motion. The effect of errors in the Earth's gravity field on a hypothetical Eos orbit is illustrated in Figure 18. This result is based on the GEM-L2 covariance matrix (Lerch *et al.*, 1985) and assumes that the Eos spacecraft is in a sun-synchronous orbit at 800 km altitude. The figure illustrates the magnitude of radial

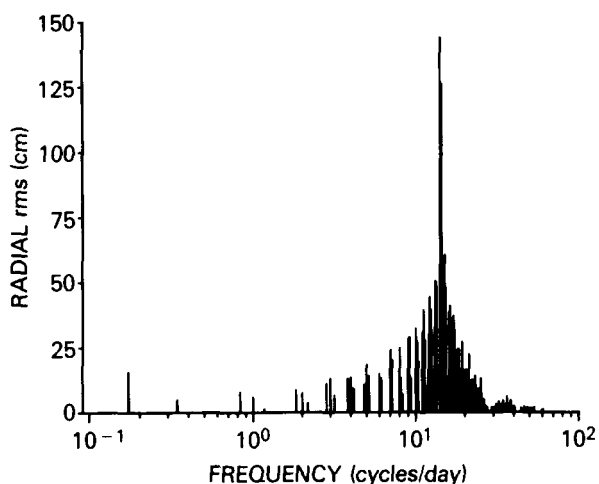


Figure 18. Root mean square of the Eos radial orbit standard deviation as a function of frequency. Long period effects not included. Based on the GEM-L2 covariance. Overall radial rms = 278 cm.

orbit perturbations, as a function of frequency, caused by uncertainties in knowledge of the Earth's gravity field. It is somewhat pessimistic because no sun-synchronous satellite data were used to generate GEM-L2. However, it should be noted that the orbit errors are of long wavelength, predominantly one cycle per revolution. The TOPEX/Poseidon gravity field improvement program sponsored by NASA and currently underway will reduce the magnitude of these errors by a factor of two to four by 1990. Further improvements in the gravity field will occur with the introduction of the GPS.

Because the dominant orbit error length scale is once per revolution, at length scales of a few hundred kilometers, it will be possible to use geometric techniques to remove long-wavelength orbit errors. Geometric techniques include removal of a linear trend from the altimeter sea surface topography through a minimization of crossover differences or by fitting individual transects to a model of the local marine geoid. Both techniques involve a least-squares minimization of residuals to select the parameters of the linear solution. However, since basin-scale orbit errors are of comparable length scale to the oceanographic signal, they cannot be removed through the use of geometric techniques of the type described here. Instead, to minimize long-wavelength orbit errors, it will be necessary to determine the orbit to the requisite accuracy through the use of tracking data of adequate accuracy and distribution. Consequently, it is useful to review the tracking systems potentially available during the mid-1990s.

Tracking Systems

During the mid-1990s four different tracking systems should be available to provide tracking data for the Eos flight systems. These include range and

range rate tracking by the TDRSS, range measurements from the ground-based laser ranging system and from the GLRS (assuming it is deployed as a component of the altimetric system), and range and range-rate measurements from the NAVSTAR GPS satellites. Geodetic and oceanographic applications of the Eos altimetric range data dictate real-time positioning of the platform with an accuracy of better than 10 m radially, and better than 10 cm in the radial component for the final geophysical data record.

These requirements eliminate TDRSS as a viable tracking option for Eos scientific applications since root-mean-square orbit accuracy is expected to be between 10 and 100 m. Moreover, there is a question concerning the viability of the complete, ground-based laser network during the Eos timeframe. While this system may be in existence, it is not known if a full global network will be operational. In addition, there will be major logistical difficulties associated with timely delivery of the laser tracking data in support of real-time global ephemerides generation. There remain, then, the GLRS and the NAVSTAR GPS as potentially viable tracking systems.

GLRS Tracking System

The GLRS to be carried onboard Eos will be a valuable instrument for verification of the altimeter height measurement accuracy. This laser could be used to range precisely (with an accuracy of order 1 cm) to retroreflectors on the surface, providing data useful both to orbit determination and for comparison and interpolation with radar altimetric range measurements. These data will provide a means for rapidly determining numerous geometric or non-dynamic orbits for the platforms. We expect that the accuracy of an ephemeris computed with these data will be limited primarily by the fidelity of the dynamic model and measurement model used for onboard processing.

The GLRS includes an ultrashort pulse, multicolor Nd:YAG laser transmitter, streak camera and high speed photomultiplier detection systems, and a submilliradian pointing system (Cohen *et al.*, 1986). GLRS is expected to have an absolute range accuracy of better than 1 cm. The system will be pulsed at a nominal rate of 10 pulses per second but will also have a burst mode capability of up to 40 pulses per second. GLRS will acquire, in a sequential process, each member of a globally distributed array of retroreflectors as each of the reflectors comes within the 70° visibility cone of the system. Extensive studies have been made of use of GLRS observations for the determination of the baseline distances between closely spaced arrays of retroreflectors arranged to measure crustal movements associated with earthquakes, tectonic plate motions, and other geodynamic and geophysical processes. These studies indicate that baseline accuracies of better than 1 cm are achievable over distances ranging from several kilometers to over 1,000 km, with the relative

and absolute position of many hundreds of targets being obtainable from only a few days worth of data. In these studies, the orbit determination problem was important, but less demanding than for altimetry because short arcs of satellite data could be used for determining the relative positions of the targets. Nevertheless, consideration of the system capabilities clearly indicates that force model uncertainties, rather than measuring capabilities of GLRS, limit the accuracy of the orbit determination for altimetry purposes. Moreover, the range uncertainty due to the incomplete modeling of the light propagation delay in the atmosphere will be reduced by an order of magnitude from present capabilities by the use of two colors (green/ultraviolet) in GLRS observations.

The most significant force model uncertainty in the orbit determination for Eos is in the gravity field. In the past, general gravity field models have been derived from a variety of measurements, both conventional and satellite-based, and from measurement systems providing different data qualities. The techniques and models used in reducing the data have employed different parameters and varying assumptions. The orbital uncertainties obtained using these gravity fields can be several meters or larger, particularly for high inclination satellites. However, by custom tailoring specific gravity models for specific satellites, it has been possible to reduce radial orbit errors to several tens of centimeters, particularly for geodetic measurements. Recent work has considerably improved this situation. The development of the latest gravity models has emphasized high-quality laser and altimeter data and consistent modeling in data reduction. Gravity model improvement is required to meet the radial orbit accuracy requirements for TOPEX/Poseidon, which requires an overall radial orbit error of less than 13 cm. Preliminary results indicate that a substantial improvement (at least a factor of 2) will be achieved in the current gravity model effort (J. Marsh, personal communication). Further improvements are expected to these preliminary results with the addition of more high-quality data and consideration of additional data types and satellites. GLRS data, obtained in the Eos mission, can provide particularly important data for further refining the gravity field and the orbit determination in the 1990s. GPS positioning will further aid the orbit determination problem. In addition to the gravity model error, the effects of atmospheric density will be a major factor that influences the accuracy with which the orbit can be computed.

With specific reference to the radar altimetry experiment on Eos, it is important to note that GLRS has an altimetric as well as retroranging capability. In fact, GLRS will operate in a narrow beamwidth, high-precision laser altimeter mode that will allow for extremely accurate calibration of the radar altimeter, and supplement the broader beam radar measurements with small spot-size, high-precision measurements over oceans, ice sheets, and land terrains. Thus

GLRS can be used as a high-resolution altimeter for detailed study of regions found to be of interest from radar altimetric surveys. Simultaneous operation of GLRS in the ranging and altimetric modes is made possible by the use of the infrared wavelength laser radiation for altimetric purposes; non-simultaneous operation in an altimetric mode can be performed at greater accuracy using the green and ultraviolet wavelengths but with the ranging pointing mirror locked at nadir. However, to accommodate the GLRS in the precision orbit determination mode, the location of the GLRS with respect to the center of mass for Eos must be known with an accuracy at the sub-centimeter level. The attitude and attitude rate must be known at the observation epochs with sufficient precision to allow the GLRS range measurement to be made at an accuracy level of 1 cm.

NAVSTAR Global Positioning System

The TOPEX/Poseidon Project will deploy an experimental GPS receiver in the early 1990s that should demonstrate the technical feasibility of meeting both real-time and post-processing accuracy requirements for Eos altimetry (Yunck *et al.*, 1985). This receiver will have the capability to generate an onboard ephemeris accurate to about 10 m for the host satellite by using P-code pseudorange. Ground processing of differential carrier phase range and delta range between Eos, the GPS satellites, and approximately six ground stations can provide sub-decimeter altitude accuracy for Eos (Yunck *et al.*, 1985). Consequently, if the GPS technology meets expectations on TOPEX/Poseidon, the Eos spacecraft should carry a GPS receiver. This would clearly satisfy both real-time and post-processing ephemeris accuracy requirements.

The GPS is a satellite-based navigation system designed to provide continuous all-weather navigation, to appropriately equipped users, on a worldwide basis. The operational system will consist of 21 satellites in circular orbits having 55° inclinations and orbit periods of 12 sidereal hours. This constellation geometry provides simultaneous visibility of four to seven satellites globally at all times. Each satellite carries an atomic clock with long-term stability of a few parts in 10^{12} . Navigation signals consisting of spread spectrum, pseudorandom noise (PRN) signals on two coherent L-band frequencies are transmitted continuously. A conventional receiver decodes the transmitted signal to obtain orbit elements, time calibration data, and measurement data.

The measurement data consists of pseudorange (time delay plus user-GPS clock offset) obtained from the clear acquisition code (C/A code) and precise or P-code data. The P-code data can be used onboard a properly equipped receiving satellite for real-time, medium accuracy (10 m) positioning of the spacecraft in the GPS coordinate frame. These data also can be telemetered from the receiving satellite to the ground,

where additional processing and more complete models will allow the position of the spacecraft to be determined to a greater accuracy.

Conventional use of the GPS system for satellite tracking is illustrated in Figure 19, which shows a receiving satellite determining its three-dimensional position and time offset from the GPS system time by measuring the apparent range to four different NAVSTAR spacecraft. The accuracy of this solution is primarily limited by: (1) NAVSTAR position error (~ 1.5 m), (2) NAVSTAR clock offsets (~ 1.0 m), (3) NAVSTAR group delay (~ 1.0 m), and (4) receiver noise (~ 1.0 m). The current uncertainty of the NAVSTAR broadcast ephemeris is an order of magnitude greater than the figure quoted above; however, 1.5 m is a reasonable assumption for the mid-1990s, providing an independent effort is undertaken to deploy and maintain a global network of GPS receivers (consisting of approximately nine stations) in much the same way that NASA has maintained the ground-based laser tracking system.

The individual NAVSTAR clock offsets, from GPS system time, are broadcast to the receiving spacecraft and are expected to be accurate to about 1 m in equivalent range error. The NAVSTAR group delay in the dual-frequency ionospheric calibration from bands L_1 and L_2 will contain a range error of about 1 m, for a maximum line of sight between GPS and a receiving spacecraft located fairly close to the horizon. Finally, receiver noise is a function of the

individual receiver, but nominal P-code range precision is expected to be about 1 m.

The root-sum-square of these errors is about 2 m equivalent range error to each GPS satellite. The effect of non-ideal observing geometry will increase this to 5 to 10 m. This will be about the limit of orbit accuracy one can expect for Eos from a direct use of GPS P-code pseudorange data. We believe this will be adequate for the real-time accuracy requirements for Eos, but it is not adequate for post-acquisition processing of the altimetric data.

The necessary improvement in estimated orbit accuracy can be realized by using differenced data (Yunck *et al.*, 1985). Figure 20 illustrates this concept of differential measurements. Here, the receiving satellite's position is determined with respect to a known receiver location by means of differential range or range-rate measurements to the NAVSTAR spacecraft. One differential range measurement yields one component of the baseline between the two receivers, contaminated by the clock offset between the two receivers. Four such measurements provide a baseline vector between the two receivers and the clock offset. The NAVSTAR clock offset and the group delay errors are identical for the two ranges and hence, cancel. Also, if the two receivers are much closer to each other than to the NAVSTAR spacecraft, the effects of a NAVSTAR position error will be greatly reduced, since it will be mostly common to both range measurements. This effect scales

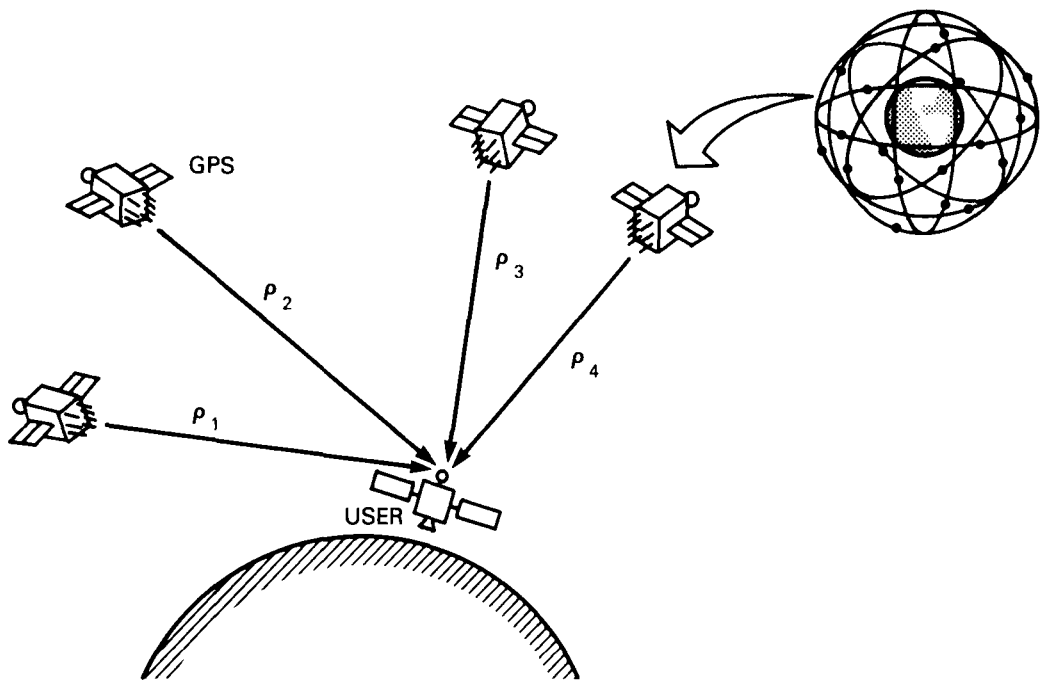


Figure 19. Direct tracking of "user" spacecraft by the GPS constellation. Spacecraft position is determined with respect to the GPS satellite's locations; principal error sources include GPS positions and timing; instantaneous position accuracy is approximately 10 m.

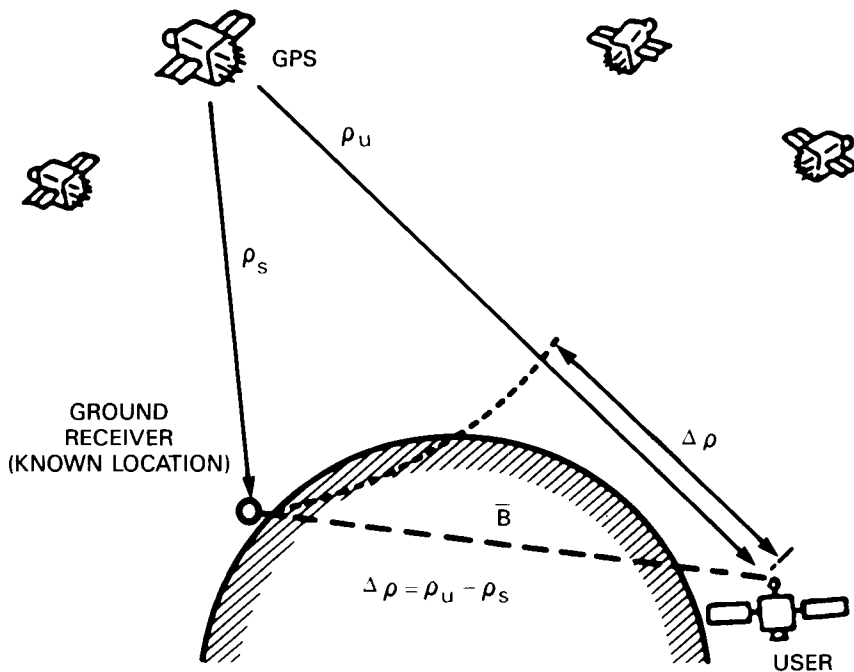


Figure 20. Spacecraft tracking using differential GPS observations. Spacecraft position is determined with respect to precisely located ground reference points; provides for substantial reduction in GPS error sources; instantaneous position accuracy is approximately 1 m.

roughly as the ratio of the baseline length to NAVSTAR altitude ($\sim 20,000$ km) and the reduction is typically a factor of 5 to 10.

If a second differential observation is taken simultaneously from another GPS spacecraft and the two differential measurements are themselves differenced, the GPS clock offset will be eliminated. This can be accomplished in the data processing procedure and imposes no additional requirements on the GPS receiver, which is already observing at least four GPS spacecraft simultaneously.

Even though the clock offsets have been removed from the differenced data, the P-code pseudorange is still not sufficiently precise to meet non-real time orbit determination accuracy requirements for Eos. One way to reduce the error from receiver noise is to move from the 10 MHz P-code to the higher frequency L-band carrier phase for range and range-rate measurements. A measurement precision of 1 percent in phase should be possible, yielding about 0.2 cm at the L_2 frequency of ~ 1.23 GHz (though subsequent differencing and other effects will reduce the precision of differential range to about 1 cm). This differential range also will contain integer cycle ambiguities which amount to about 19 cm per cycle at L_1 (~ 1.58 GHz) and 24 cm per cycle at L_2 . Resolution of this problem for satellite applications seems unlikely, and continuous carrier phase change which can be converted into a doppler measurement or a range difference measurement also is a potential orbit determination tool. These data are not affected by cycle ambiguities and can yield subdecimeter ra-

dial position accuracy for a low Earth-orbiting spacecraft.

If the ambiguity problem can be solved, then differential range data between GPS and the ground stations can be used for short arc (< 10 min) determination of Eos platform positions. These short arc solutions are essentially geometric and are not highly dependent on dynamic model accuracy. A simpler solution is to use the differential doppler data (or range change) in a long arc (> 2 satellite revolutions) to solve for a platform's state vector. However, the accuracy of the long arc solutions is critically dependent on the accuracy of the mathematical models used to describe the satellite's motion. For Eos, the major model errors will be in the Earth's gravity field and the atmospheric drag models. Moreover, none of these solution techniques requires GPS ground stations to track an Eos platform.

The real-time orbit determination requirements for Eos can therefore be met with a GPS receiver that has an onboard capacity to process P-code pseudorange in a navigation filter. The ephemeris of Eos computed by the receiver should be downlinked in the telemetry stream together with related GPS information, including P-code pseudorange and phase from bands L_1 and L_2 , accumulated carrier phase from bands L_1 and L_2 , and the navigation message. The data rate from the receiver will be about 700 bps, continuous. In order to meet the non-real-time orbit accuracy requirements for Eos the GPS receiver onboard the platform should be able to measure P-code range to a precision of 60 cm for 1 second

integration times. It should measure carrier phase for both the L_1 and L_2 bands to a precision equivalent to 1 cm in range for a 1 s integration time. The receiver should have the capability to continuously track and count carrier phase (no cycle slips) for a minimum of four NAVSTAR spacecraft, simultaneously. In addition, uncalibrated systematic biases in carrier phase between GPS satellites should be less than 1 cm. These are hardware-related biases that do not include multipath (which will be calibrated separately) or GPS clock offsets (which will be eliminated by the solution procedure). Time tag accuracy for the data should be about 0.5 μ s.

Based upon GPS capabilities and the foregoing analysis, we believe the GPS system can satisfy both the real-time and post-processing orbit accuracy requirements for all Eos platforms. Clearly, the platform carrying the GLRS will have additional information from which non-dynamic, geometric ephemerides can be calculated as well. Using GLRS data alone, we expect the post-processing orbital accuracies to be of the same order as those derived for Seasat (i.e., approximately one-half meter).

VERIFICATION

The objective of the verification process is to determine the performance of the complete measurement system including elements of the satellite, sensors, and communication links as well as the sensor and geophysical file algorithms and associated reduced data. The final geophysical data set consists of verified measurements of height, significant wave height and wind speed (derived from backscatter coefficient), and total electron content. The verification process should determine the accuracy of these geophysical measurements.

The Eos verification process should begin prior to launch and continue for some period after launch. The data processing system must be fully functional prior to launch to verify that algorithm and data flow are meeting specifications on the appropriate time lines. A reasonable goal would be to have the altimetric data processing system operational 6 months prior to launch.

During the first few months after launch, verification and engineering assessment should be the primary activities. Based on past experience the initial verification will require about 6 months. These activities should continue throughout the mission at a "lower level" after the initial verification period. When the algorithms, data products, and processing procedures have been verified, production of GDR begins. Thereafter, modifications and updates of the algorithms may be made, if necessary, subject to Project-established review and approval procedures. Verification after the initial period should consist primarily of continuing to monitor the quality of the geophysical measurements and the precision orbits. If this monitoring activity reveals unexplained accu-

racy deviations, then a reverification effort similar to that performed during the initial testing period will be necessary.

Prelaunch Verification

Prelaunch verification consists of determining that all algorithms to produce the GDR data have been encoded and checked and that ground-based data collection instruments and communication lines are functioning properly. Test cases for algorithm assessment should be provided by the organization that develops the algorithm.

Prelaunch readiness should be determined through a complete, end-to-end test of the ground data systems, including measurement and processing functions. This should also include exercising all interfaces with the Project Operations Control Center, the TDRSS facilities, and the Eos data processing system.

Postlaunch Verification

The initial 30 days of the mission following instrument power-up should be dedicated to verifying that the spacecraft, sensors, communications links, and ground equipment are functioning according to engineering specifications. During this 30-day engineering assessment period, the collection of data for geophysical verification will begin. An intensive verification of the geophysical parameters, height, wave height, and wind speed should be carried on for the first 6 months after launch.

The height measurements should be verified by an Eos Altimeter Instrument Team through comparison of the altimetric height measurement with ground-based laser measurements, in a manner similar to that used for Seasat (Kolenkiewicz and Martin, 1982). Wave height, wind speed, and total electron content should be verified by comparison with *in situ* measurements. Total electron content should be verified by comparisons with results obtained from an incoherent scatter radar located in proximity of a coastal region, while wave height and wind speed should be verified with the use of satellite-linked buoy systems.

The Eos satellite will be placed in an exact repeat track orbit which passes over the calibration site. This site could be an island such as Bermuda (which was used for Seasat, see Kolenkiewicz and Martin, 1982) or it could be a properly instrumented offshore platform. In either case, the calibration site should be instrumented with a laser to provide precise range measurements to the Eos spacecraft. The GLRS could be used to verify the altimeter height measurement by ranging to targets on an island or an off-shore platform to centimeter accuracy. Consequently, it is important that GLRS fly on the same platform with an Eos altimeter if a ground-based laser system is

not available. This is important from both an altimeter verification viewpoint and to provide supplemental data for precise orbit determination. The laser and/or the laser target arrays must be surveyed to establish their height relative to mean sea level.

The calibration site also should be instrumented with a tide gauge and should be equipped with meteorological instrumentation to measure surface parameters such as atmospheric pressure, temperature, and water vapor pressure. Also, an off-shore buoy array, located along the platforms' ground trace, should acquire wind speed and wave height data for use in the verification process.

Verification Monitoring

Following the initial verification period a verification monitoring activity should be maintained throughout the duration of the mission. During this phase a periodic check of the altimetric height accuracy could be accomplished with the GLRS using the techniques described for the intensive calibration period.

Other Techniques

Other methods also could be used to monitor altimeter accuracy including crossing arc differences, analysis of repeat track residuals, and waveform analysis. Statistics on these quantities should be maintained in the altimeter data processing facility. Consistency of the altimeter height measurement accuracy also can be monitored by using a technique developed for measuring variations in global mean sea level (Born *et al.*, 1986). This technique provides a means for monitoring long-term drifts in the altimeter height measurement bias. If an apparent change in global mean sea level is detected it must be determined if this is actually a change in mean sea level or a drift in the altimeter height measurement bias. Differentiation between these two possibilities should be obvious because of the magnitude and time scale of the apparent sea level shift or from ancillary data related to internal bias drifts in the altimeter itself. If the source of the change in apparent sea level is not obvious, a recalibration using the laser should determine whether or not a drift in the altimeter height measurement accuracy has occurred.

VI. DATA SYSTEMS

The challenges of creating an appropriate data system for Eos include the complexities introduced by the needs of the altimetric system as a whole. Treating the entire measurement system from spacecraft end-effectors, through to and including the research scientist, suggests that there are considerations onboard as well as on the ground. However, given the flexibility of the envisioned Eos data and information system, outlined by the Eos Data Panel (Chase *et al.*, 1986), we believe that the majority of altimeter-specific data system problems will be adequately addressed. With this in mind, we describe in this section a rationale for onboard and ground-based processing as well as the needs for ancillary information to fully exploit surface topographic measurements made by the Eos altimetric system.

ONBOARD DATA PROCESSING

Assuming that the Eos altimeter is patterned after the TOPEX altimeter the following scenario should be followed for onboard processing. The altimeter will be two-channel, one at K_u and one at C-band. The C-band data is used to correct the K_u -band height measurement for charged particle refraction effects; consequently, only the height's difference from the K_u -band height word is required. The PRF will depend to some extent on altimeter design and orbital altitude but will be in the neighborhood of 4,000 pulses per second at K_u -band and 1,000 pulses per second at C-band. The return power from these pulses is sampled within the signal processor at approximately 128 points. In the case of TOPEX/Poseidon, only 64 waveform samples are telemetered to the ground, which represents a factor of 2 reduction via onboard processing. These waveform samples probably will be recorded every 50 ms, which is roughly a 200:1 reduction. In addition to the waveform samples, significant wave-height data ($H_{1/3}$) and height data obtained from the half power point of these waveforms is recorded every 50 ms. For TOPEX/Poseidon, the onboard microprocessor is an Intel 80186 that has approximately 128K 16-bit words of memory.

As a result of onboard processing, the radar altimeter data rate will be about 8,000 bps except in the calibration mode when additional C-band waveforms are recorded and the data rate is approximately 12,000 bps.

Onboard GPS Processing

The GPS receiver-processors onboard Eos platforms should collect precision GPS navigation data, use these data to compute an ephemeris for the platform, and format these data for transmittal to the ground by the Eos communication system. In the

case of TOPEX/Poseidon the onboard architecture proposed includes a single master microprocessor and five receiver microprocessors dedicated to each of five tracking channels (Geier *et al.*, 1985). We recommend a similar configuration for Eos.

The master microprocessor performs the moding and sequencing logic function, which essentially schedules and controls the execution of all functions during operations. In addition, it provides the interface with uplinked commands and performs the GPS satellite selection from among the visible set of NAVSTAR satellites. Other functions include maintenance of a current set of almanac and ephemeris data for use in navigation processing and satellite selection and measurement data compression of the pseudo- and delta-range measurements. The master microprocessor computes the position of the GPS satellites from their current set of orbital elements as well as the position velocity and clock error for the Eos platforms. Finally the data must be interfaced to the telemetry system for transmittal to the ground.

The receiver microprocessor handles the input and output from the master microprocessor. This includes, for example, the output of pseudo- and delta-range measurements and demodulated system data. The receiver processor performs the necessary calculations to support GPS signal acquisition and tracking and controls the C/A code generation and P1 and P2 tone tracking as well as L2 carrier phase.

Based upon the TOPEX design, we estimate the master microprocessor core storage requirements to be less than 50K 16-bit words and 8K 16-bit words for each receiver microprocessor (Geier *et al.*, 1985).

GROUND-BASED DATA PROCESSING

After Eos telemetry data are received at the central processing facility they will be sorted, merged, time tagged, and overlaps will be removed. The telemetry data are then broken into separate channels (decommutation) and converted to engineering units. The data may then be sent to a payload operations control center where they are Earth-located with a precision orbit and spacecraft attitude information is added to the file (Level 1A).

The next phase of processing is referred to as sensor file (Level 1B) processing. Here the altimeter data are edited, compressed, and corrected for instrument and spacecraft effects. These include corrections for time tag bias and for spacecraft attitude. The first computation for the sensor file is the identification of blunder points. These are outlying data that must be omitted instead of being used in any final product without special processing, which is

generally not available in the sensor file. Usually, blunder points occur from bad telemetry where bits of data are lost or inserted. They can also occur from the onboard altimeter tracker response during the first part of acquisition, in coastal areas, or during severe attitude transitions.

A critical function is correctly time tagging each data point. A number of factors are associated with the accurate timing of the data. All the functions associated with correctly time tagging the telemetry burst gate that is activated when a frame of data enters the telemetry block are accomplished within the sensor data record (SDR) processing. In addition there are time lags not accounted for in the SDR that are related to internal delays in the altimeter (Lorell *et al.*, 1982). These are corrected in the sensor file processor.

Corrections need to be made to height measurement, automatic gain control setting, and significant wave height because of limitations in the altimetric hardware, the ocean return input models, and the tracker design. For example, details on instrument and spacecraft corrections for the Seasat altimeter are given in Hancock *et al.* (1980). In the case of Seasat no reprocessing of waveform data was performed on the ground for use in generating the GDR. However, for ice and land applications considerable processing of waveform data on the ground was required. Therefore, the GDR basically was valid only over ocean.

It is possible that in the case of Eos, processing of the waveform data in the sensor file processor will occur. This would be a significant computational burden. However, as indicated in Hayne and Hancock (1982), the waveform is sensitive to at least six different parameters: amplitude, track-point, sea surface significant wave height, noise baseline, sea surface skewness, and spacecraft off-nadir attitude angle. Reprocessing of the waveform data to yield improved estimates of these parameters results in corrected values of height, $H_{1/3}$, and attitude, and it eliminates many of the look-up table corrections made for Seasat. The question of waveform processing versus look-up tables for parameters determined onboard Eos must be resolved by study at a later date.

After completion of the sensor file processing, the data are input to the geophysical file processor. Here the data are corrected for media and surface effects and the necessary ancillary data to make the altimeter data scientifically useful are added (Level 2 processing). Media corrections include path delays due to refraction of the ionosphere, and wet and dry troposphere. The ionospheric correction will be based on total electron content in the nadir column, which is determined by differential altimeter range measurements at two frequencies.

The ocean tide algorithm interpolates the results of input tidal models. These models could be the Schwiderski (1980) or the Parke-Hendershott model (1980). The solid Earth tide, which must be added

to the ocean tide, uses the position of the sun and moon to determine the astronomically induced solid Earth tides. In addition, the height of the marine geoid above a specified reference ellipsoid generally is supplied on the GDR.

Thus the GDR contains sea surface height relative to the reference ellipsoid; however, height above the marine geoid is also readily available. The number of calculations necessary to produce the GDR depends heavily on whether or not waveform data are processed. If waveform data are not processed on the ground a VAX 11/780-class machine will probably be adequate. If waveform data are processed, a mainframe (mini-super class) will probably be required.

Ground-Based GPS Processing

The essential elements of a GPS ground system would be a set of 6 to 10 ground stations, a central processing site, and a communications link between them (Melbourne, 1984). The ground stations should be located uniformly around the globe, exact locations being dependent upon issues such as security, communications, ease of maintenance, and unattended operation (Sonnabend, 1982). Each GPS station would consist of a receiver, a tropospheric calibration assembly, a communication terminal, and a shelter and support facility. Each ground terminal would relay to the central processing facility the phase data derived from the GPS satellite observations and other ancillary information. The communication link could be via satellite or ground line with about 1 Kbps data rate from each station. The data from an Eos platform would be sent to an altimeter processing site from the Eos control center. These processing facilities could be co-located.

At the processing site, the data streams from the ground and flight systems would be combined yielding the appropriate metric data sets for navigation as well as other information for network monitor and control functions. The metric data streams, after being validated, edited, calibrated, and phase corrected, would be transferred to an orbit determination processor where the orbit of an Eos platform would be updated. It is assumed that precise ephemeris information for each NAVSTAR satellite is available from another source and does not have to be recomputed for this application.

The software system required to process the GPS data to produce a precise ephemeris for the Eos spacecraft will be large (~100,000 lines of code) and will best function on a super computer. However, geometric fitting techniques are under investigation that may mitigate the need for a super computer (Yunck and Wu, 1986). Software systems under development to process GPS data include the GEODYN system at GSFC, the UTOPIA system at the University of Texas at Austin, the GIPSY system at JPL, the MITES system at MIT, and the CELEST system at NSWC.

Eos platform orbits should be computed within a few days to one week after data acquisition. This delay allows adequate time to collect all tracking data and to compute and adjust the orbit estimates, as necessary. The ephemeris data would then be transmitted to an altimetric data processing facility. Here the data would be used to compute sea surface height and to Earth locate the altimetric geophysical data records.

Summary

Data handling and processing advancements may be needed to meet the demands of precision orbit determination and altimetric data processing. The simultaneous measurement of high-precision elevation information from multiple spacecraft or over a finite swath width has not been accomplished to date. Many advantages can be derived from additional information if it can be produced in a reasonable timeframe. For example, crossing points created by descending and ascending orbital ground traces from the three platforms could be used in joint-solution precision orbit determination. If the orbital segments are closely spaced in time (within a day or two), then the ocean's structure will likely not have changed significantly. Large differences between the topographic heights measured at each of the crossing points must be due to orbital errors. Minimizing the differences between the ascending and descending ground trace measurements will help eliminate these orbital errors.

NETWORKING

Telecommunications networks will play a vital role in ensuring the scientific and technical success of altimetric measurements. As currently conceived, the Eos data and information system will support a full spectrum of network services ranging from packet switched 9.6 kbps links to computer network subsystems operating at 1.5 mbps to 6.3 mbps. These speeds are more than adequate providing that the links are established between appropriate facilities.

The data produced by the Eos platforms will flow through a ground data receiving station prior to delivery to an instrument operations control center. This center will have the responsibility for reducing the data prior to dissemination to the research community and the archives. The key facility for the altimeter will thus be its associated control center. All pertinent ancillary and corroborative information must therefore be linked directly (and electronically) to the altimeter operations control center, ensuring the timely reduction and subsequent dissemination of reduced data.

Given the rates of data production and volumes of data involved, we recommend that the links between pertinent data repositories and the altimeter

operations control center should operate as packet switched networks with minimum speeds of 9.6 kbps.

ARCHIVAL

A Level 1 data record is the most fundamental (i.e., highest reversible level) data record that has significant scientific utility, and is the foundation upon which all subsequent data sets are produced. Accordingly, the Eos Data Panel has recommended that all Eos data should be reduced to at least Level 1 and archived at this level (Chase *et al.*, 1986). We support this recommendation in terms of the primary, long-term archival data and further recommend that all altimeter data be routinely processed and archived in Level 2 (geophysical data records) format, since the data have little scientific utility at lower processing levels.

Based upon experience with previous altimetric data sets, we expect that algorithms and processing techniques will continue to evolve and improve with time. With this in mind, we further recommend that the Level 2 archive be periodically reviewed by the altimetry instrument team and the holdings be updated with newly produced Level 2 data when improvements warrant. Since the Level 2 archives represent a significant volume reduction over the total Level 1 holdings required to produce them, the impact on archival storage of the Level 2 data sets will be minimal.

OTHER DATA REQUIREMENTS

Beyond the specifics of data and information systems noted above, there will be a continuing need for other sources of information pertinent to the reduction and analysis of altimeter data. Among the needed ancillary information are tidal data, water vapor measurements, surface wind fields, laser altitude information, and atmospheric pressure measurements.

Tidal Data and Models

To make precise measurements of ocean currents from altimetric observations of sea surface elevations, we need to remove those signals caused by ocean and Earth tides. The amplitude and spatial scale of ocean tides are of the order of 1 m and 1,000 km, respectively, whereas those of Earth tides are 0.2 m and 20,000 km, respectively. Present day tidal models can predict ocean tides with a root-mean-square accuracy of 10 cm for ocean tides and 2 cm for Earth tides. These models include those of Schwiderski (1980; ocean tide), Parke and Hendershott (1980; ocean tide), and Melchior (1978; Earth tide).

The residual errors due to ocean tides are still too large for ocean circulation studies. However, the currently planned TOPEX/Poseidon Mission, whose inclination angle will be optimal for determining ocean tides from altimetry, will be able to directly measure geocentric ocean tides with an accuracy of about 2 cm. The resultant amplitude and phase functions can then be used to make tidal corrections for other spacecraft altimetry data sets via improved models. Tidal corrections for altimetric observations using state of the art tidal models should be made available to researchers using the Eos altimetric data. We therefore recommend that research and development of tidal models be continued in anticipation of this need during the Eos era.

Radiometer Data

Water vapor in the atmosphere retards the velocity of radio signals, causing a radar such as the altimeter to over-estimate platform height by roughly one-half meter. Further, the water vapor column content can also produce fictitious slopes of the sea surface if uncorrected. Large-scale, time-averaged corrections for the influence of water vapor can be made from climatological data, but these typically are insufficiently accurate for high-precision altimetry. The best possible means for correcting altimetric measurements is by using microwave radiometer measurements made near the 22.3 GHz water vapor absorption band. The AMSR proposed for Eos deployment is capable of providing the requisite measurements.

We assume that the AMSR processing facility will determine the integrated water vapor content in the nadir column corresponding to the altimeter main beam direction. This information can be converted into altimeter path length correction and transmitted to the altimeter data processing facility for inclusion in the GDR. This should be a minor computational burden on both the AMSR and altimeter processing facilities.

Wave Height and Wind Data

Wave heights are of intrinsic value particularly for operational purposes. Although deducible from the received altimetric pulse, wave height introduces an error in the estimated position of the mean sea surface because the troughs of ocean waves tend to be better reflectors than the crests. This results in the centroid of the returned power distribution being shifted away from mean sea level toward the troughs of waves. This electromagnetic bias introduced by waves appears to be of order 2 percent, although in seas that are not fully developed, the bias appears to range upward to 3 percent. This suggests that wind speed itself will be required for accurate estimates of the electromagnetic bias, hence accurate production of Level 2 geophysical data records.

Wind field data produced by the Eos scatterometer will provide an adequate estimate of surface wind velocities from which the electromagnetic bias errors can be corrected. We thus recommend that the altimeter instrument team have ready access to reduced (Level 2 or 3) scatterometer data records. Since it would be impractical for all of the scatterometer data to be produced at Level 3 for correction of the altimeter data, we recommend that the scatterometer data be reduced to Level 3 only over the specific geographic site selected for altimeter verification purposes.

Laser Ranging Data

As we have noted, the addition of laser altimeter measurements to the Eos radar altimeter data base will be of significant value to several scientific disciplines, glaciology being a prime example. Similarly, we have noted the benefits to precision orbit determination that we anticipate from the laser retroranger data. In both cases, we expect the laser instrument to provide very accurate measurements of the height of the spacecraft above the surface of the Earth. Since these measurements are not prone to entirely the same set of error sources, the laser measurements provide an independent means of verifying computations leading to variables of interest both scientifically and operationally.

There are several potential problems associated with the LASA-R instrument as currently defined. These include the size of the optical telescope, expected flashtube longevity, and pertinent to this section, data rates (the other potential difficulties are discussed in the next chapter of this report). As we have indicated, the total expected data stream (including GPS records) from the Eos radar altimeter will be about 12 kbps. To this, we must add the laser data that is produced at a rate approaching 500 kbps! The laser altimeter and retroranger therefore has the capability not only to dominate but also to totally swamp the TDRSS downlink.

To prevent this, the duty cycle of the laser instrument must be carefully monitored and onboard data compression schemes must be employed. While this will clearly solve the potential downlink capacity limitation, it will also generate a rather significant post-acquisition data merger problem. Careful attention must therefore be paid to both mission planning and the design of the ground processing elements that will handle these data.

Atmospheric Pressure Data

As atmospheric pressure varies over time scales ranging from a few days up to a year, the sea surface tends to respond hydrostatically. This response is

frequently referred to as the “inverse barometer effect”: for a 1 mbar increase in atmospheric pressure, the sea surface is depressed correspondingly by 1.01 cm. Because surface pressure over the oceans is not routinely available from spacecraft, it must be inferred from wind measurements and a paucity of ship reports. Current estimates of the accuracy of these data are of the order of ± 3 mbar, although it may be much worse in relatively remote and untraveled regions. Since this error varies little over space scales of hundreds to thousands of kilometers, its influence will not overly influence measurements of the meso-scale field. Therefore, we recommend that the Eos data and information system provide access to *in situ* observations available on the international Global Weather Network, to help correct for the effects of variable atmospheric pressures.

Temperature and Water Vapor Pressure

The wet tropospheric pathlength correction, due to changes in the index of refraction caused by water vapor in the atmosphere, can be calculated in two different ways. The first uses information on the total vertically integrated atmospheric water vapor content in the spacecraft nadir column based on measurements by the AMSR. The second option uses surface values of the atmospheric temperature and water vapor pressure based on data fields that could be supplied by the FNOC. The computation of dry tropospheric correction, due to changes in the index of refraction caused by the dry component of the atmosphere, requires values of the surface atmospheric pressure. Global data bases of these variables also could be supplied by FNOC. Again, we recommend that the Eos data and information system provide access to these data.

VII. INSTRUMENT SYNERGISM

In this chapter, we explore the synergistic uses of various instruments in the context of satellite altimetry. There are several instances where other instruments in the Eos payload produce data sets of value to the reduction and analysis of altimeter data and in increasing the overall scientific utility of the Eos altimetry data set. The microwave radiometer, laser retroranger, and scatterometer are cases in point.

MICROWAVE RADIOMETER

As we have noted, the Eos microwave radiometer (AMSR) provides a means of correcting the satellite height measurement for the total integrated water vapor content of the atmosphere by providing radiation measurements at frequencies close to the water-vapor absorption band (22 GHz). Beyond this, we have discussed the combination of altimeter and microwave radiometer measurements being used to measure characteristic rain properties.

Specifically, rain in the atmosphere above the surface also reflects the altimeter's pulse, the reflected power being a function of the rain rate (viz. Figure 12) and the proportion of the radar beam being filled by rain cells. By observing the reflected power at two heights (using the so-called "rain gates"), one near the surface and one a few kilometers above the surface, it should be possible to measure both rain rate and rainfall area. By combining the microwave radiometer signal, which measures emission from rain, with the radar signal, which measures scatter from rain, we expect to obtain a more precise estimate of rain rate.

Essentially, emission, scatter, and rain rate are all different moments of the rain distrometric (drop size) distribution. This distribution is accurately specified on average by two parameters; two separate moments, measured by emission and scatter, define a third parameter, rain rate. Experimental accuracies approaching 10 percent (Ulbrich and Atlas, 1978) have been achieved in the field although it is reasonable to expect that the practical difficulties that will be encountered in making these measurements from low Earth orbit will likely degrade these accuracies to some extent.

GEODYNAMIC LASER RANGING SYSTEM

The GLRS, also known as LASA-R (viz. Curran *et al.*, 1986), can provide auxilliary information pertinent to both the reduction and scientific interpretation of the radar altimetric data. The discussion in this chapter is limited to a few issues that are not emphasized in the LASA Report. First, for nadir altimetry the GLRS signal-to-noise ratio needs to be large enough to allow the tracking of typical ice,

ocean, and solid Earth target surfaces. The receiver aperture has been specified as being 18 cm. In a recent paper by Bufton *et al.* (1981), the photoelectron levels for signal and background noise received through a 50 cm telescope at 700 km altitude were calculated to be 488 and 3.9, respectively, for an ice sheet target. Similarly, they were calculated to be 38 and 0.34 photoelectrons, respectively, for an ocean target. At a similar altitude, the expected GLRS signal levels would be less by a factor of 8, because of the smaller telescope aperture. The GLRS values must also be reduced by an additional factor of 5 because the transmitted energy per pulse is specified to be 10 mJ rather than the 50 mJ used by Bufton *et al.* (1981). While ice sheet targets would likely be strong enough to be tracked, oceanographic applications will probably require a larger optical receiver than those indicated in the LASA Report (Curran *et al.*, 1986).

Another issue of importance is the lifetime of the GLRS laser. The exact combination of applications that the GLRS is to support will dictate the usable lifetime devoted to each application. If we assume, for example, that 2 full days of mission orbits are necessary to obtain ice sheet topographic data over both polar regions, and that these data will be collected on 3-month intervals over a 3-year period (24 days of data collection), then the number of orbits used for this application will represent about 2.2 percent of the total number of orbits during that time period. At a pulse repetition frequency of 10 pulses per second (pps), this results in 6.9 million pulses. If the total number of pulses for the laser is 10 million, then the remaining 3.1 million provide the capability for 7 minutes of 1 pps retroreflector ranging per orbit on 46.6 percent of the total orbits. No time would remain for geologic applications. Consequently, tradeoffs of this kind will be needed for the various applications to which the GLRS is devoted.

Techniques for assimilating the complementary radar altimeter and GLRS data sets must be developed. The lower pulse repetition frequency of the laser altimeter and its shorter lifetime must be weighed against the larger footprint and higher repetition frequency of the microwave system in the development of a comprehensive sampling strategy that involves both instruments.

From a technical viewpoint, the co-location of the radar altimeter with a laser retroranger is appropriate and beneficial for both instrument systems. The GLRS, has two stated measurement roles. In addition to nadir altimetry, the laser would be capable of ranging at prescribed directions toward retroreflectors located on the Earth's surface. This pointing capability requires a spacecraft attitude control subsystem that is capable of absolute angular accuracy to within a few arcseconds.

Figure 16 shows the variation of range to mean sea level at the antenna boresight as a function of roll angle for an 800 km altitude and a 50 km off-nadir beam displacement. A roll angle of only 0.1° causes a 90 m range error for this geometry. Accuracies on the order of an arcsecond, however, result in roll angle errors in elevation of the order of 10 cm. This is the order of range precision needed to do oceanographic altimetry. Therefore, we find technical advantages to deploying the laser and radar altimeters on an Eos platform.

The GLRS ability to determine spacecraft ephemeris at the centimeter level in the retroranging mode greatly enhances the absolute accuracy of the radar altimeter by removing any meter-level uncertainties in spacecraft position. The inclusion of a laser retroreflector on the Eos platform adds another degree of refinement to the precision orbit determination capability of this suite of instrument systems. Ground-based laser ranging systems can use this reflector to determine the Eos orbit to a few centimeters of uncertainty; the GLRS can perform the same service from orbit by observing the ground-based retroreflectors. The combination will define the Eos orbit with unprecedented accuracy and the resulting Eos topographic measurement will benefit from this refined orbit.

SCATTEROMETER

We have noted the use of scatterometer-derived wind fields to predict surface waves that are sub-

sequently used to correct for the altimeter's electromagnetic bias. Scatterometer wind fields coupled with altimeter-derived surface height measurements are also of scientific utility in the quantitative study of surface layer dynamics.

We also note that a main objective of Eos is to develop and verify oceanic models that can be coupled with atmospheric models to predict the evolution of the Earth's climate system. Since the currents in the upper ocean, accounting for the bulk of the kinetic energy of the ocean, are driven by wind stress and thermodynamic forcing of the sun and atmosphere, to make progress toward this goal we must undertake quantitative studies of wind-driven surface layer dynamics. Even the thermal forcing of the surface boundary layer involves the wind field since the downward mixing of heat in the surface layers and the evaporation of water are strong functions of wind speed. Thus, the surface wind field, derivable from a radar scatterometer, coupled with altimeter measurements of the surface height, provide key pieces of information for quantitative ocean circulation studies.

Eventually, we hope to calculate ocean currents with useful accuracy from a knowledge of winds over the ocean. Simultaneous global observations of the winds obviously go a long way toward better understanding of the ocean's response to wind and lead to the development of global ocean-atmosphere models with which we can address changes in the Earth's physical climate.

VIII. RECOMMENDATIONS AND CONCLUSION

There are many well-documented uses for precise altimetric measurements that we have touched upon in this report; they extend from basic research in the Earth sciences to applied problems that impact our daily lives. These problems include those directly related to significantly improving our understanding of the oceans as a whole (including ice-covered regions), the physical climate system, solid Earth land masses, offshore energy production, commerce, coastal zone problems, communications, and national defense. Based upon our experience with previous satellite-borne altimeters, we believe that the accuracies and precisions needed to address these problems can be achieved from Eos platforms, thus perpetuating the high-quality data set expected from TOPEX/Poseidon and providing new data for basic research in the Earth sciences and for operational tasks. On this basis, we summarize in this section our recommendations and conclusion for altimetric measurements from Eos platforms.

Eos ALTIMETRIC SYSTEM

We have demonstrated that high-precision surface topographic data cannot be obtained from one single spaceborne instrument alone. Rather, to meet the requirements of the research and operational communities, careful consideration must be given to the concept of an altimetric instrument system. As we envision an Eos altimetric system, it would consist of TOPEX-class radar altimeters deployed on each of the three Eos platforms. Additionally, these instruments would be supported by GPS receivers, a microwave radiometer, laser retroranger or retroreflectors, an attitude control system, onboard data system, *in situ* observations of various geophysical variables, a complete ground-based data and information system, and an Eos Altimetry Instrument Team.

We have also noted the scientific and technologic synergies that exist between the radar altimeter and other planned Eos instruments (i.e., AMSR, GLRS, SCATT, ADCLS) as well as the scientific advantages of a three-radar system. Thus, while weight, power, volume, and fiscal considerations might otherwise preclude the joint deployment of all four instruments on each platform, the addition of a single TOPEX-class altimeter to each Eos platform provides a ready means of ensuring the requisite scientific synergy while yielding only very minimal impact on the spacecraft.

TOPEX-Class Altimeter

We recommend the use of TOPEX-class radar altimeters aboard Eos platforms since they are a fourth-generation instrument that is well developed both scientifically and technologically. Further, we

note that by using this instrument, Eos will be at an advantage relative to its prime goal of perpetuating planned research data bases, in this case the accurate and precise measurements from the Ocean Topography Experiment. We also note that since the TOPEX/Poseidon spacecraft will likely be launched in 1991, reproduction of its basic radar altimeter and supporting subsystems will presumably have the smallest fiscal impact on the overall Eos Program, even if minor changes are made.

Finally, we believe that given the lifecycle of Eos and the recommendation of the Eos Science Steering Committee to capitalize on technologic advances, the Eos Program should foster the development of multibeam radar altimetry as a prospective future replacement for the TOPEX-class Eos instruments.

Multibeam Research and Development

The developing technologies of multibeam radar altimetry hold a great deal of promise for an instrument system that could replicate existing capabilities while providing entirely new information for scientific research (e.g., a direct measurement of vorticity). We recognize that there are at least three technologic approaches that could be developed and suggest that a study should be undertaken to assess which methodology holds the greatest promise technologically, scientifically, and fiscally. Furthermore, based upon the results of this study, we recommend that a prototype instrument should be developed and tested.

In addition to the technologies involved with the production of narrow multiple radar beams, other key technological problems will need study before multibeam altimeters could be reliably implemented as a component of the Eos Altimetric System. The multiple beams will, of course, necessitate the use of multiple range trackers. The requirement for topographic mapping over the Earth's ice sheets and land masses will require that the tracking schemes used be highly adaptive.

The backscattered waveform from the Earth's surface, whether from water, land, or ice, must be sampled electronically to know its shape and temporal position after the transmission of the radar pulse. The rather predictable shape for ocean and ice backscattered waveforms can be used to position the tracking gates with the proper spacing and widths. Over land, it is likely that regions of steep slopes and large roughness lengths will be mapped. For a radar altimeter to function properly under these conditions, it will be necessary for the spacing and widths of the tracking gates to be modified in near-real time; this is the level of adaptive tracking that we believe will be necessary. Consequently, we recommend that a

research and development effort should be undertaken to address this issue.

Global Positioning System

We recommend that GPS receivers be deployed aboard each Eos platform to provide sufficient information to allow precision orbit determination to be undertaken for each platform. TOPEX-class experimental GPS receivers should have the capability of providing 10 m onboard orbital accuracies and post-processing should yield subdecimeter accuracies for the radial orbit component. Since this would be consistent with Eos altimetry goals, we recommend the inclusion of these GPS receivers assuming they perform as specified during the Ocean Topography Experiment.

Microwave Radiometer

We recommend that Eos radar altimeters be deployed with either the AMSR or a separate, stand-alone microwave radiometer subsystem. The purpose of the microwave radiometer is to provide emission information for both rainfall measurements and for water vapor path length corrections for the radar. AMSR can serve these functions when deployed with the radar altimeter; otherwise, a small three channel radiometer with bands centered around 37, 21, and 18 GHz should be employed.

Laser Retroreflector/Retroreflector

We recommend that the Eos radar altimeters should be deployed with either the GLRS or a separate, stand-alone space-based laser retroreflector. The purposes of a joint deployment are both scientific and in terms of platform precision orbit determination. Assuming an onboard laser retroreflector is utilized, it will only address pertinent precision orbit determination and altimetric calibration issues; and it carries the concomitant problem of maintenance and upkeep of the existing ground-based laser tracking network.

The GLRS instrument has been discussed in this report from the perspective of an instrument that can provide valuable corroborative data for the microwave altimeter. This instrument is defined for ranging to retroreflectors placed on the Earth's surface. If it is additionally designed to operate as a nadir pointing altimeter, the utility of both the radar altimeter as well as the laser system will be further enhanced. The combination of radar altimeter and laser altimeter provides a calibration check when each is ranged to the same horizontal surface. If the surface is not horizontal, the two altimeters provide a direct measurement of slope. For uneven topography such as ground terrain or ice sheets, a laser altimeter provides important surface roughness information on a spatial scale not possible with the broader-beam radar altimeter.

This roughness information will be helpful in analyzing the full character of the radar return pulse waveforms, which includes information on the surface roughness well away from the narrow swath of laser altimeter footprints. Used together in this way, the laser and radar altimeters are a beautiful example of instrument synergism. We therefore recommend that this design modification be adopted for the GLRS instrument.

Design modifications for the laser may also include an increase in the aperture of the receiving telescope and an increase in transmitted power, providing a means to receive a reasonable number of photoelectrons per return pulse. A Shuttle-based experiment of an appropriately designed laser altimeter will help answer these questions relative to solid Earth and ice sheet surfaces. If a larger aperture is required for the nadir-looking altimeter, this can be most effectively accomplished by enlarging the aperture of the receiving telescope while maintaining the size of the movable mirror for the pointing laser and surrounding this mirror by a larger mirror (for nadir altimetry) that would be fixed in place to fill the full aperture of the receiving telescope.

Beyond these proposed design modifications, we recommend careful study of the laser flashtube lifetime issue. Given the current state of technical development, some very severe tradeoffs would be required and it remains unclear from a cost-benefit standpoint if the added scientific and operational utility will balance the heretofore undetermined costs involved with developing a laser system with suitable design life.

Attitude Control Subsystem

Spacecraft attitude and rate of attitude change must be known at observational epochs if GLRS range measurements are to be made with an accuracy of 1 cm. We therefore recommend that a separate attitude control subsystem be included with the altimetric payload if the GLRS is deployed as a component of the system. An active attitude control system is preferable since it would minimize systematic errors; we recommend that this subsystem be designed with a minimum attitude maintenance capability of 1 arcsecond relative to the local vertical.

Requisite *In Situ* Observations

We note that there is a host of *in situ* observations that would be of significant scientific value to a researcher actively engaged in Eos-sponsored studies. Because of their scientific significance, we recommend that provisions be made to support their acquisition for Eos-sponsored researchers. Autonomous acquisition can best be accomplished by deploying the ADCLS.

Additionally, the Eos radar altimeter data processing task will require a set of *in situ* observations

to support both the verification program that we recommend and the reduction of the altimetric data to GDR. These observations include atmospheric pressure and temperature, sea state, wind velocity, and water vapor pressure. Some of these data are available from sources such as NOAA and FNOOC while others must be obtained specifically within the geographic region used for verification purposes. We recommend that the Eos Program provide ready access to the requisite data, preferably electronically.

Eos Data and Information System

We concur with and fully support the recommendations of the Eos Data Panel concerning the need for a complete data and information system. We recommend that those specific components dedicated to the acquisition and production of altimeter data, including both hardware and software, be installed and fully functional at least 6 months prior to launching the first platform. We further recommend that this portion of the system be thoroughly tested during this 6-month period and that any noted deficiencies be remedied before launch.

Since the Eos Data Panel recommended that Eos-derived data beyond Level 1 be processed only on request, we hereby request that all altimeter data be routinely processed to Level 2. We further recommend that a select subset of both AMSR and scatterometer data be routinely reduced to Level 2 over the specific geographic region that will be used for verification purposes.

OTHER CONSIDERATIONS

There are numerous ancillary considerations that affect the quality and scientific utility of altimetric measurements; we have touched upon some within this report, while others have gone unmentioned. We discuss here two germane issues for early consideration by NASA.

Altimetry Teams

We strongly recommend that the scientific community be involved in the development and subsequent operation of Eos altimeters from the outset and throughout all subsequent activities, since the data will be acquired, transmitted, processed, and delivered for scientific purposes. We recommend that researchers also be given an oversight and review responsibility, and suggest that this might best be accomplished through the establishment of an Altimetry Instrument Team.

Further, because of the critical dependence of scientifically useful altimetric data on precision orbit determination, we also recommend that a closely allied Precision Orbit Determination Team

be established to work with both the Altimetry Instrument Team and Project personnel.

Orbit Selection

We have discussed the advantages of multiple spacecraft each with a satellite altimeter for mapping mesoscale features. We have also indicated that it would be far preferable from a precision orbit determination standpoint if these platforms were all deployed at the same orbital altitude. The TOPEX Science Working Group has documented the advantages of both high-altitude (over 1,300 km) and low-altitude (around 800 km) orbits. In considering all of these factors together, we recommend that careful consideration be given to sun-synchronous "frozen" orbits as a viable alternative to purely circular orbits. Assuming that other instruments cannot tolerate a modestly eccentric orbit, the current scenario, which utilizes three platforms at 824 km in circular, sun-synchronous orbits should be adopted as the nominal baseline for Eos.

Platform Structural Rigidity

We are concerned with the novel new structures that are being proposed for the Space Station polar platforms, hence the Eos spacecraft. These platforms promise to be the largest autonomous structures ever placed into orbit by NASA (Butler *et al.*, 1987). Significant levels of flexure in these structures seems inevitable and the new modular designs may, in fact, produce an even greater level of flexure than rigid structures used in other satellites. Periodic or aperiodic flexure of the structure will introduce contamination in the altimeter measurement that will be difficult to detect and remove. Consequently, we recommend that Project personnel become closely involved in Space Station Project activities, ensuring that the best interests of the Eos altimetric system are considered.

Antenna Location

We recommend that the radar altimeter antenna be positioned with the minimum possible moment arm from the platforms' center of mass. By positioning the antenna as closely as possible to the center of mass, undetected attitude variations and effects of platform flexure will be minimized. This will, in turn, minimize any time-dependent errors (which are difficult to model) resulting from these factors.

Center of Mass Knowledge

Assuming that GLRS is jointly deployed on at least one platform with a radar altimeter, its location relative to the center of mass of the spacecraft must be known to better than 1 cm if the resultant data are to be used for precision orbit determination.

CONCLUSION

Based upon the wealth of documentation supporting the utility of high-precision altimetric measurements (which we summarize in this report) and our analysis of Eos goals and platform capabilities, we believe that Eos can achieve its prime goal of perpetuating research data sets (in this case surface topographic data) for studies of Earth System Science. We therefore recommend that serious consideration be given to the inclusion of a high-precision Altimetric System, based upon a TOPEX-class radar instrument, on all Eos platforms. Further, we recommend deployments of AMSR, scatterometer, and GLRS, so that at least one of these instruments can be operated synergistically with an Eos radar altimeter

on each of the platforms, thereby maximizing the scientific utility of Eos spacecraft. We also recommend that an appropriate data system be designed, implemented, and operational at least 6 months prior to launch. We further recommend that the development of multibeam radar altimeter technology be continued since the promise of this emerging technology for new and otherwise unobtainable measurements is high. Finally, and perhaps most important, we recommend that the scientific community be involved in the design and implementation of the Eos Altimeter System; this involvement might best be accomplished through the establishment of active Altimetry Instrument and Precision Orbit Determination Teams with representatives from appropriate scientific and engineering disciplines and from the operational sector.

APPENDIX A: ERROR BUDGET FOR Eos ALTIMETER HEIGHT MEASUREMENTS

A number of error sources will affect the accuracy of sea surface topography obtained from height measurements made with the Eos altimeter. These error sources are briefly described and an error budget for the Eos system is given in this section. The information given here is based on experience gained from the Seasat, GEOS-3, and Geosat missions as well as analysis that is being performed for the TOPEX/Poseidon mission.

MEASUREMENT ACCURACY

Ocean surface topography is recoverable from two fundamental quantities: the altimeter measurement of height and the estimated radial component of the orbit. To achieve the greatest possible accuracy in the sea surface height, certain ancillary measurements must be used to correct for atmospheric and surface effects that corrupt the altimetric measurements. These corrections are not perfect, and their contributions to the total error budget must be considered in an analysis of the complete measurement system. Table A.1 presents a list of the dominant error sources that will contribute to the Eos sea surface topography error budget.

Table A.1. Altimeter Height Measurement Error Sources

Altimeter	Orbit
Instrument noise	Drag
Bias draft	Radiation pressure
Time tag	Earth radiation
Tracker bias	GM
Media	Gravity
EM bias	Earth and ocean tides
Wave skewness	Station location
Troposphere (dry)	Third order ionosphere
Troposphere (wet)	Troposphere
Ionosphere	Clocks

ALTIMETER INSTRUMENT ERRORS

Instrument Noise

As indicated by Table A.1, the dominant error source for the altimeter will be instrument noise. Figure A.1, taken from Lorell (1982), present plots of data noise for the Seasat altimeter as a function of significant wave height. Results shown here are based on 10-per-second data. However, because of correlations both in the instrument and those introduced by surface effects, the data noise for 1-per-second data is reduced only by about a factor of 2 rather than a factor of 10. In-flight data from Townsend

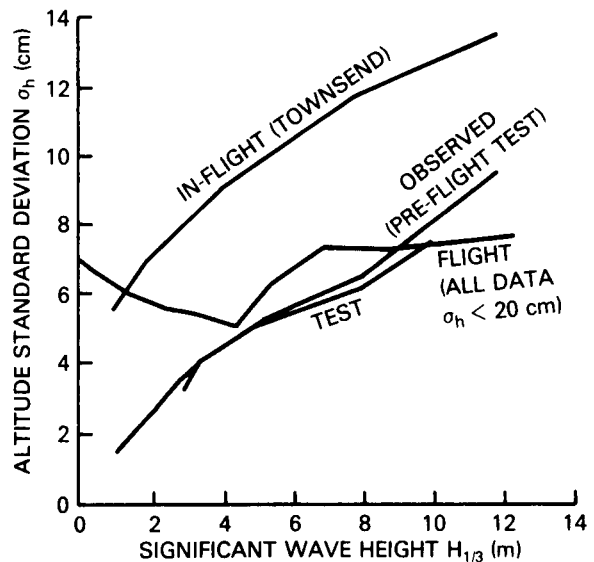


Figure A.1. Seasat data noise for 10/s data. In-flight data from Townsend (1980) are for one pass over a storm. Results for all flight data have data edited for $\sigma_h > 20$ cm and are taken from Lorell (1982).

(1980) are for a single transect over a storm. Results for all-flight data have data edited for $\sigma_h > 20$ cm and therefore will be somewhat optimistic. Consequently, actual performance of the Seasat altimeter lies somewhere between the in-flight result from Townsend and the all-flight data. Based on anticipated performance for the TOPEX/Poseidon altimeter and the results for Seasat and Geosat, noise level for the Eos altimeter should be 2 cm or less for 1 second averaging times and low to moderate sea states. If a multibeam altimeter is flown on Eos, measurement noise for the off-nadir beams will depend on parameters such as antenna diameter and boom length (Bush *et al.*, 1984) but should be less than 5 cm.

Bias Drift

A height bias in the altimeter range measurement may occur because of possible internal drift due to environmental effects (e.g., temperature, aging, voltage variations, etc). Any internal drift in instrument bias should be monitored with an onboard calibration system to within 2 cm.

Time Tag

The uncertainty in instrument time delays, as well as the spacecraft-to-ground communications system, may result in a data time tag error. This will introduce a height error equivalent to $\dot{h} \cdot \Delta t$, where \dot{h}

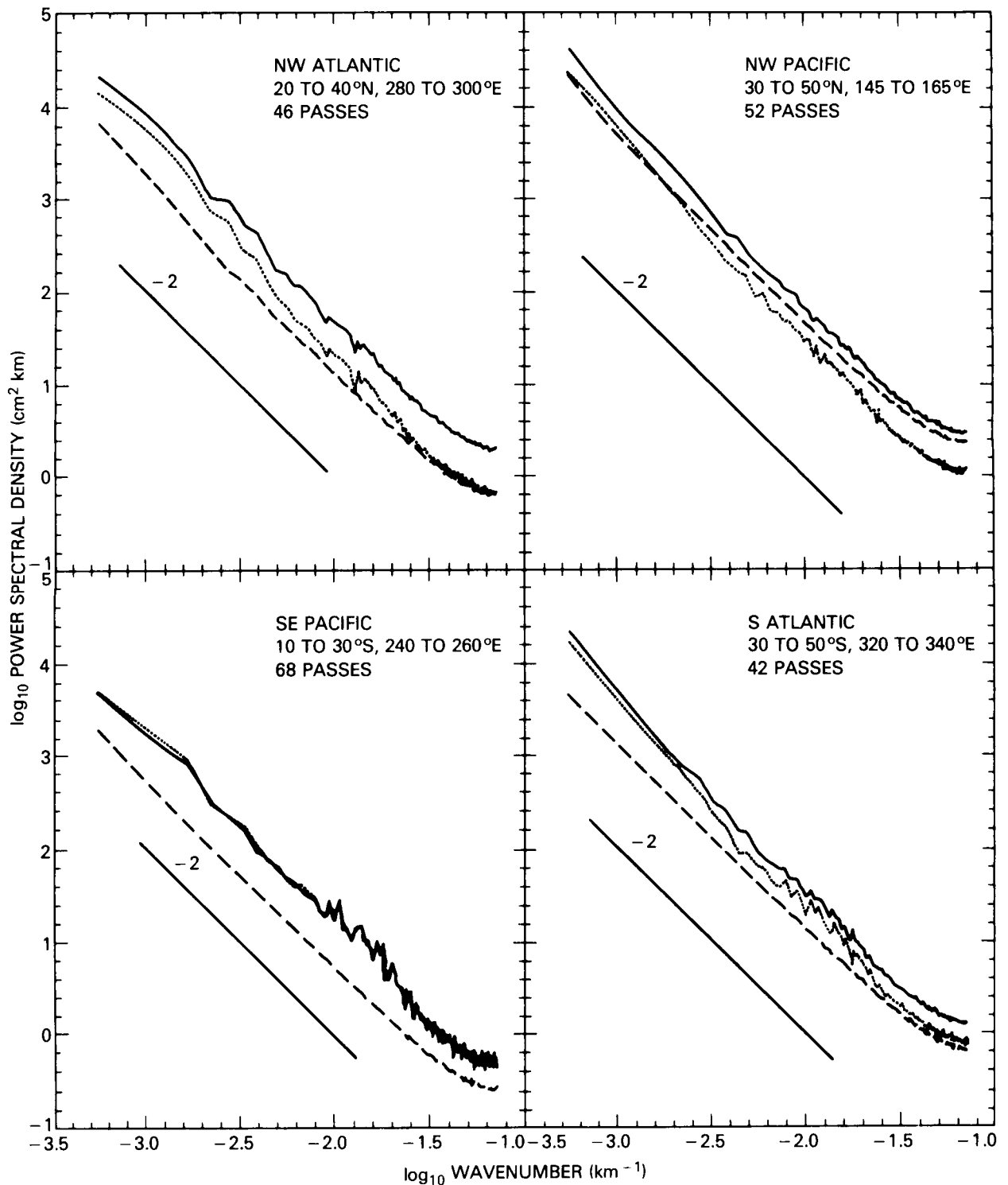


Figure A.2. Power spectral density of water vapor for various geographic areas of the world. The solid line represents SMMR data; the dashed line is data from FNOC; the dotted line is the difference between the SMMR and FNOC data bases. The minus two power law function is plotted for reference purposes.

is the radial velocity of the spacecraft relative to the surface and Δt is the time tag error. The Eos time should be accurate to 100 μs , and for typical maximum altitude rates of 50 m per second, this will result in a negligible 0.5 cm error. Based on the Seasat experience, the time tag error can be verified at the millisecond level using crossing arc analysis (Marsh and Williamson, 1982; Schutz *et al.*, 1982). A millisecond is equivalent to 5 cm in height error for an altitude rate of 50 m per second.

Tracker Bias

Another potential error source associated with the altimeter is the correction that must be made to the onboard tracker determination of height. This correction accounts for off-nadir pointing of the altimeter and the effects of sea state. Because of limitations inherent with onboard processing, some simplifications generally are made in the waveform processing algorithm used by the onboard tracker. A correction is made in the ground processing system to compensate for these simplifications. It is assumed that these corrections will reduce tracker bias to the centimeter level.

MEDIA ERRORS

Electromagnetic Bias

Electromagnetic bias occurs because the troughs of ocean waves tend to be better reflectors than the crests. As a result, the centroid of the returned power to a radar altimeter is shifted away from mean sea level toward the troughs of the waves. The magnitude of this bias is thought to be in the neighborhood of 2 percent of the significant wave height at frequencies of 13.6 GHz (Walsh *et al.*, 1984; Choy *et al.*, 1984). Assuming that the bias can be modeled to within 1 percent, a significant wave height of 2 m results in a 2 cm error contribution.

Skewness Error

It is assumed, for the onboard tracker algorithm, that the ocean surface elevation has a Gaussian distribution. Hence, skewness in the surface elevations will introduce errors into the tracker-determined height measurements. However, these errors will be second order relative to the effects of $H_{1/3}$, which dominates the portion of the waveform used for height detection. If no attempt is made in the ground processing to correct the height measurement for skewness effects, a surface skewness of 0.1 will result in approximately a 1 cm altitude error. For a discussion of electromagnetic and tracker bias vis-a-vis Seasat, see Hayne and Hancock (1982), Born *et al.* (1982), Lipa and Barrick (1981), and Douglas and Agreen (1983).

Troposphere

The path lengthening experienced by electromagnetic waves propagating through the atmosphere can be expressed as the line integral of the refractive index. The integral may be represented by the superposition of a "dry" and a "wet" component. A tutorial discussion of the atmospheric effects on altimeter height measurements is given by Goldhirsh and Rowland (1982).

Assuming that the FNOC global pressure fields are used to provide a dry component correction, the uncertainty in this correction should be less than 1 cm. In the case of Seasat, comparing dry component corrections obtained by using surface pressure from 19 globally-distributed radiosonde flights with that obtained by using FNOC predictions of atmospheric pressure at sea level resulted in a standard deviation of 0.59 cm (Tapley *et al.*, 1982b). The error in height correction due to uncertainty in atmospheric pressure is approximately given by:

$$h_d \cong 0.228 P_o$$

where h_d is in centimeters and P_o is the error in atmospheric pressure in millibars.

The path length correction necessary to account for the wet component of the troposphere can be as large as 30 to 40 cm in the tropics. This correction was at wavelengths that range from a few hundred to thousands of kilometers; however, most of the energy in the wet component is at wavelengths greater than a few thousand kilometers. This is illustrated in Figure A.2, which displays the spectrum of water vapor corrections derived from Seasat Scanning Multifrequency Microwave Radiometer (SMMR) measurements over several different geographical areas.

Figure A.3 illustrates several profiles of Seasat SMMR results compared to the wet tropospheric correction computed from global FNOC fields of surface water vapor pressure and air temperature. Note that while there is signal at mesoscale wavelengths (50 to 300 km) in the SMMR results, it is generally of small amplitude (<10 cm) and shows little repeatability over these repeat-track profiles that are 3 days apart. A comparison of SMMR and FNOC derived results across an ocean basin are illustrated in Figure A.4, which shows both water vapor range corrections and their difference across the Pacific.

Ionosphere

Intervening free electrons in the ionosphere will introduce a group delay in the altimeter pulse that is proportional to the columnar electron content and the inverse square of the pulse frequency. The standard unit for the electron content is referred to as the Total Electron Content Unit (TECU) and is equal to 10^{16} m^{-2} . This translates into a range correction of 0.214 cm per TECU at 13.6 GHz. The dynamic range of TECU is 50 to 100 TECU night-to-day depending

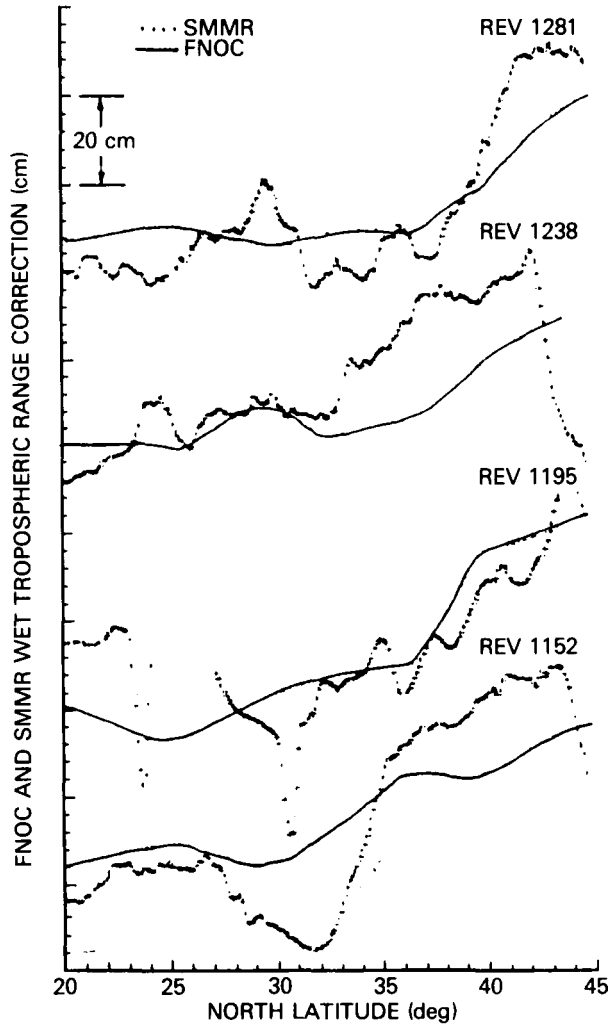


Figure A.3. FNOC and Seasat SMMR wet tropospheric range correction in the North Atlantic. These results are from repeating ground tracks separated by 3 days in time. Note that while mesoscale signals with amplitudes on order 10 cm exist, they do not persist from pass to pass (Born, 1982).

on the F10.7 solar flux level. Eos will be flying during the mid-1990s, which will be a low in the 11-year solar cycle, as illustrated in Figure A.5, which is taken from the NOAA/USAF Space Environment Services Center weekly publication of the Preliminary Report and Forecast of Solar Geophysical Data. Figure A.5 shows the Zurich smoothed sun spot number, which is highly correlated with F10.7 GHz solar flux and total electron content, for three complete solar cycles plus results from the current cycle. Figure A.6, taken from Green *et al.* (1980), clearly illustrates the seasonal and diurnal variations in TECU for Goldstone, CA, a northern hemisphere mid-altitude location.

The relationship between range correction and TECU (Callahan, 1984) is:

$$\Delta = 40.3 (\text{TECU})/[f (\text{GHz})]^2$$

Assuming Eos flies a TOPEX-class altimeter the frequency of the primary channel will be 13.6 GHz and

$$h = 0.218 \text{ TECU}$$

A model based on monthly mean TECU should have an accuracy of 30 to 50 percent (Callahan, 1984). There are also short-length scale fluctuations in the ionosphere of smaller amplitude. An attempt to quantify short-length scale in the atmosphere variations is shown in Figure A.7, which also is taken from Callahan (1984). As seen from this Figure, variations in TECU on the mesoscale will be less than 10 percent of the mean TECU. In any case, assuming

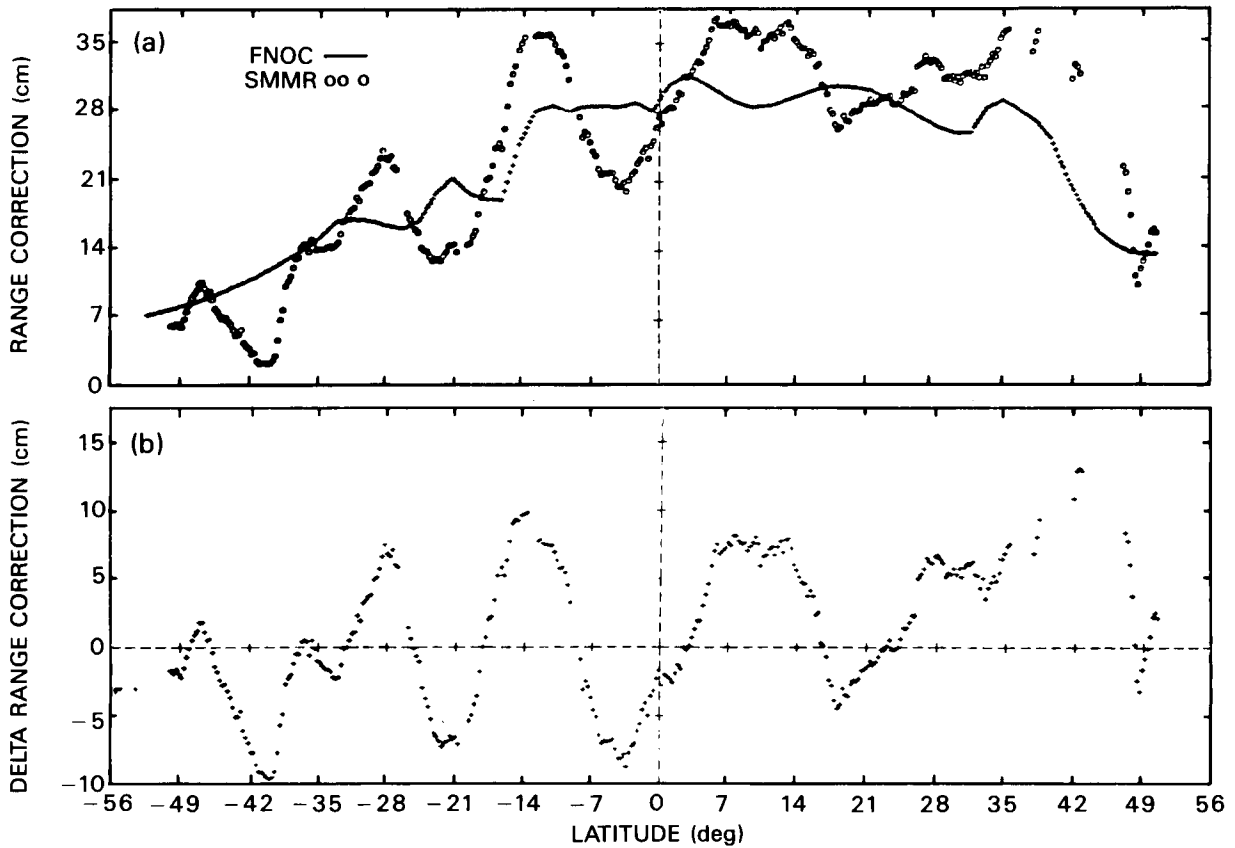


Figure A.4. SMMR and FNOC water vapor range corrections across the Pacific for Seasat Rev. No. 1172 (Born, 1982).

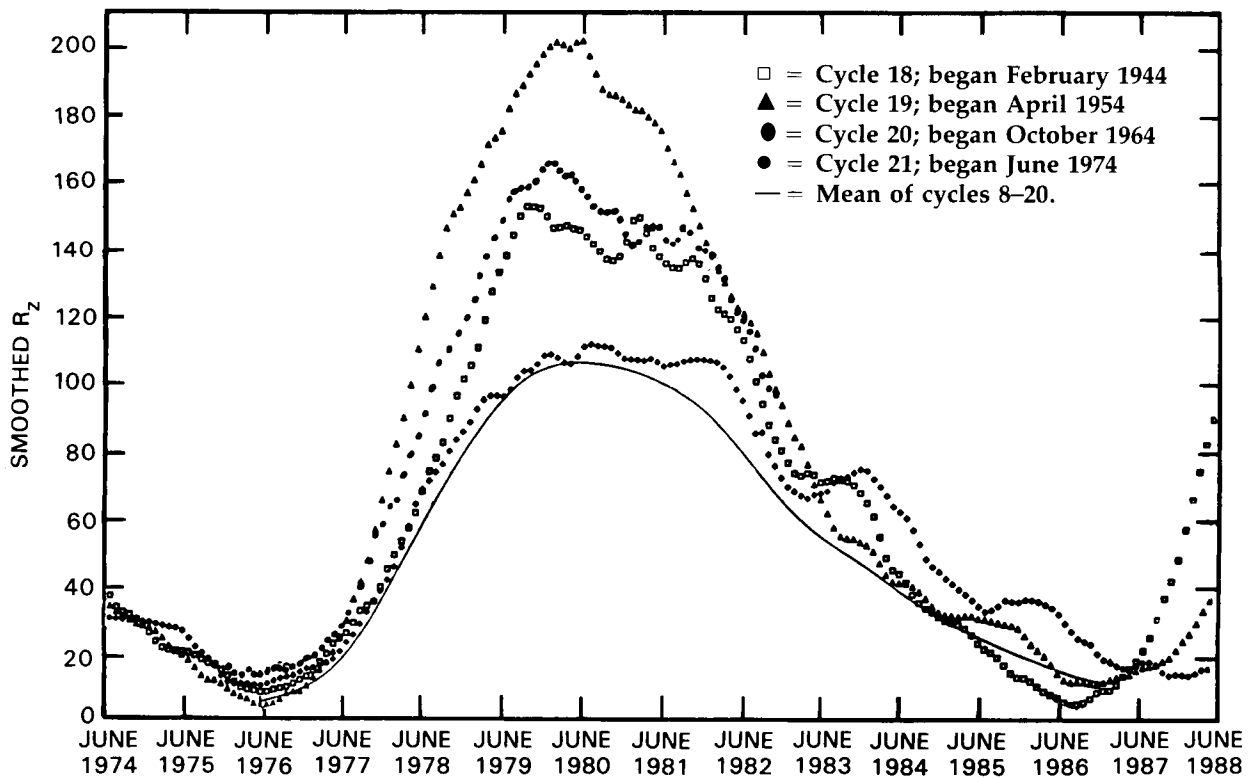


Figure A.5. Zurich Smoothed Sun Spot Number for solar cycles 18, 19, 20, and 21; derived from NOAA/USAF Space Environmental Services Center data (the initial minima in each cycle has been phase shifted to coincide with the initial minima in cycle 21).

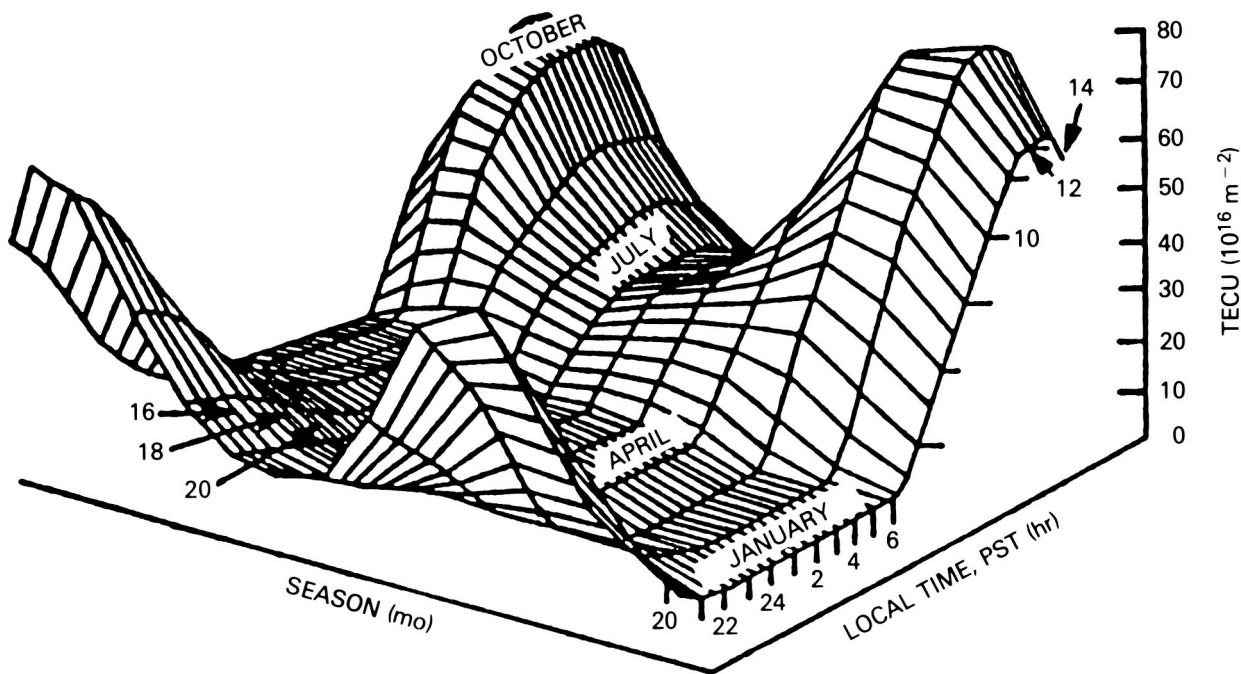


Figure A.6. Ionospheric activity—1979 monthly average total electron columnar content profile for Goldstone, CA (Green *et al.*, 1980).

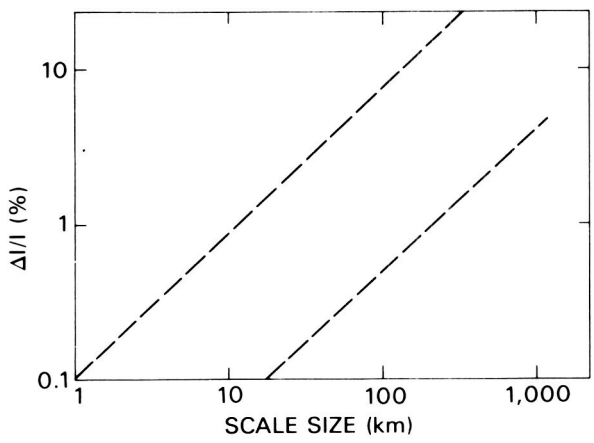


Figure A.7. Ionospheric electron columnar content fluctuations as a function of scale size (there is a factor of 3 uncertainty in the data; there is little data for scales greater than 100 km; most data corresponds to measurements from equatorial or auroral regions).

a dual frequency altimeter for Eos, the contribution of ionospheric errors should be below the centimeter level.

ORBIT ERRORS

Orbit determination (OD) accuracy depends on the uncertainties in the dynamic models that govern spacecraft motion and on the type, accuracy, and amount of tracking data. Dynamical model elements that affect OD accuracy are listed in Table A.1. They include atmospheric drag, the modeling of which requires knowledge of atmospheric density and the area and mass properties of the spacecraft. Other forces that must be modeled accurately are solar radiation pressure and Earth-reflected radiation pressure as well as the gravitational attractions of the Earth, including those due to solid Earth and ocean tides.

In addition to dynamic model parameters, the observations also must be accurately modeled. Assuming that Eos utilizes a GPS receiver, subdecimeter

radial positioning of the spacecraft should be possible. Table A.2 illustrates the anticipated orbit error for Eos using a GPS receiver and a dynamical orbit determination approach.

SUMMARY

Table A.2 summarizes the error budget for measurement of ocean topography using Eos altimetry.

The major assumptions associated with this error budget are summarized in the table. The column titled "Wavelength of Error" indicates approximately the shortest length scale associated with an error of the indicated amplitude. Based upon this analysis, it appears likely that a radar deployed aboard properly equipped Eos platforms will be capable of perpetuating the high-quality data set anticipated from the Ocean Topography Experimental spacecraft, TOPEX/Poseidon.

Table A.2. Eos Altimeter Measurement Uncertainty*

Error Source	Uncertainty (cm, 1σ)	Wavelength of Error (km)
Altimeter		
Instrument noise	2	(many days)
Bias drift	2	20,000
Time tag	1	200–1,000
Tracker bias	1	
Media		
EM bias	2	200–1,000
Skewness	1	200–1,000
Troposphere (dry)	1	1,000
Troposphere (wet)	1	200
Ionosphere	0.5	1,000
Orbit		
Gravity	5	10,000
GM	1	10,000
Atmospheric drag	2	10,000
Troposphere	1	10,000
Solar radiation pressure	1	10,000
Earth albedo	1	10,000
Earth and ocean tides	1	10,000
Station coordinates	2	10,000
Station and spacecraft clock	1	10,000
GPS ephemeris error	2	10,000
rss 8 cm		

*Major Assumptions For Baseline Mission:

1. GPS tracking system—9 ground stations
2. Limited tuning of gravity field with Eos tracking
3. Altimeter data averaged over 1 s
4. $H_{1/3} = 2$ m, wave skewness = 0.1
5. Instrument noises shown is for nadir beam
6. 800 km altitude
7. No anomalous data, no rain
8. ± 3 mbar surface pressure from weather charts
9. 100 s spacecraft clock

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