The Future of Spaceborne Altimetry
Oceans and Climate Change

A Long Term Strategy

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The Future of Spaceborne Altimetry

Oceans and Climate Change

A Long-Term Strategy

A Report Prepared by the Future Altimetry Working Group

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PREFACE

Over the past 15 to 20 years, there has been mounting concern worldwide over future climate change, whether man-induced or natural. With that concern has come a growing recognition that the ocean is a central, and conceivably, dominant element in determining climate. For example, it is believed that the ocean carries one third to one half of the heat from equator to pole, a flux which renders the mid-latitudes of the Earth habitable; the ocean is believed to be a major sink of the constantly increasing human production of carbon dioxide and other greenhouse gases; and analyses of cores from the sea floor and the icecaps strongly suggest that during the past, when the Earth's climate was very different, the ocean circulation was also radically different.

A dominant scientific issue is that too little is known of the present-day ocean circulation, how it operates, and to what extent it is stable, or undergoing secular changes. A major problem for scientists attempting to produce forecasts of future climate useful for policy decisions is that these forecasts have no credibility or utility if they do not adequately account for the present ocean circulation and changes. Today, realistic models of the ocean are impossible to construct owing both to uncertainty over the governing physics, chemistry, and biology, and an inadequate ability to prescribe the present state of the system. Global, continuous observations of the ocean are required.

Until the advent of high-accuracy altimeter systems, oceanographers had no means for observing the motion of the ocean as a whole, on a global scale. To understand such a complex, turbulent fluid, one requires repeated, high-accuracy, carefully calibrated observations of the entire system, sustained over the time scales of change. Without altimetry, the central methods remain ship-board ones. Given the slow speed, labor intensity and great expense of ship operations, oceanography has been mainly limited to regional studies. With the growing concern over climate change, the need for a technology capable of studying the ocean as a whole has become imperative. In a remarkable coincidence of requirements and technological development, scientifically useful altimeters have become available just as the need is paramount.

Altimetry has become a focus of global change studies in the ocean because it is the only such tool available to us. Its potential for providing the required understanding has been demonstrated repeatedly through the altimeter missions of the past 15 years. Thus, through a combination of clever engineering and scientific ingenuity, altimetric measurements produced the first maps of global mesoscale variability; the first estimates of the absolute, large-scale circulation on a global, synoptic basis; and the first estimates of the very large-scale oceanic variability. Substantial progress has been made on the transfer of this surface information into understanding of the vertical structure of the ocean circulation through the use of dynamical models. In addition, altimetry has led to great new understanding of the Earth's gravity field, topography and geophysical structure of the sea floor, and the interior of the Earth in general; and it will allow for a real-time monitoring of the wave field at the sea surface.

The other element of the climate system having a very extended memory, and thus capable of exerting strong controls on climate is the cryosphere (ice). Observing the state of the major ice sheets of Greenland and the Antarctic is a

problem not unlike that of observing the ocean–one of large-scale, extremely accurate, repeatable coverage. Here too, altimetry appears to be the only method available that is capable of determining with the required accuracy whether these ice sheets are growing or shrinking, how fast they are redistributing their mass and the mechanisms of their dynamical evolution. As with the ocean, a knowledge of cryospheric behavior is central to any predictive capability for the climate system.

In the report that follows here, an attempt is made to lay out both the scientific rationale, and the technical elements of effective altimetric systems. Such systems are one of the more successful complex measurement systems ever devised. Altimetric measurements rely on a cluster of instruments which cannot be accommodated at the required precision on any satellite-of-opportunity. Much effort has gone into the use of existing data, and into plans for future altimeters. This very large undertaking is a reflection of the essential, central role these measurements will play in reducing the current extreme uncertainty of the future behavior of our climate.

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PREFACE

Les changements climatiques, naturels ou anthropogéniques, font l'objet d'un intérêt croissant au niveau international et ce depuis 15 à 20 ans. Il est de plus en plus généralement reconnu que les océans jouent un rôle central, et très probablement dominant, dans le système climatique. Par exemple, on estime que l'océan transporte de 30 à 50 % de la chaleur de l'équateur vers les pôles, ce qui rend le climat nettement plus hospitalier aux moyennes latitudes. On pense également que l'océan absorbe une grande partie du dioxyde de carbone et autres gaz à effet de serre qui sont produits, en quantités croissantes, par l'activité humaine. L'analyse de carottages effectués sur les fonds marins et les calottes polaires indique que, dans le passé, lorsque le climat de la Terre était très différent du climat présent, la circulation océanique était aussi radicalement différente.

Aujourd'hui, nous connaissons encore peu de choses sur la circulation océanique, comment elle fonctionne, dans quelle mesure elle est stable ou subit des variations séculaires. C'est un problème majeur pour les scientifiques qui s'efforcent de prévoir l'évolution du climat afin de guider des décisions politiques qui engagent l'avenir. Leurs prévisions ne seront ni crédibles ni utiles tant qu'elles ne prendront pas en compte de façon adéquate la circulation océanique et ses variations. A l'heure actuelle, il est impossible de construire un modèle d'océan réaliste à cause, d'une part, des incertitudes qui existent encore sur les phénomènes physiques, chimiques et biologiques qui gouvernent le système océanique et, d'autre part, à cause de notre incapacité à déterminer l'état actuel de ce système. Nous avons donc clairement besoin d'observations globales et continues de l'océan.

Jusqu'à l'avènement de systèmes altimétriques précis, les océanographes n'avaient aucun moyen d'observer le mouvement des océans à l'échelle du globe. Pour comprendre l'évolution d'un milieu fluide turbulent aussi complexe que l'océan, il est nécessaire de disposer, de façon globale, de mesures répétées, précises et parfaitement calibrées durant une période qui couvre les échelles de temps du système observé. En l'absence d'altimétrie, les méthodes de base demeuraient les méthodes d'observation à la mer. Vu la lenteur, le coût et la difficulté de ces mesures, la plupart des études océanographiques restaient régionales. Avec l'intérêt croissant suscité par l'étude des changements climatiques, le besoin d'une technologie adaptée à l'observation de l'océan global est devenu impératif. Dans une coïncidence remarquable entre le besoin et les possibilités des technologies nouvelles, des altimètres performants arrivent sur le marché juste au moment où le besoin est énorme.

L'altimétrie nourrit déjà une recherche abondante sur les changements globaux de l'océan parce que c'est la seule technique globale qui soit disponible aujourd'hui. Sa capacité à fournir les éléments d'observation dont nous avons besoin a été démontrée à de multiples reprises lors des missions altimétriques des quinze dernières années. Ainsi, grâce à une ingénierie brillante associée à l'ingéniosité des scientifiques, l'altimétrie a fourni les premières cartes globales de la variabilité océanique à la mésoéchelle, les premières déterminations synoptiques de la circulation absolue et globale et les premières estimations de la variabilité de la circulation à très grande échelle. Des modèles dynamiques ont également permis de réaliser des progrès

substantiels quant au transfert de l'information altimétrique de surface en termes de compréhension de la structure verticale de la circulation océanique. En guise de sous-produits majeurs, l'altimétrie a énormément fait progresser notre connaissance du champ de gravité terrestre, de la topographie et de la structure géophysique des fonds marins et de l'intérieur de la Terre, en général. L'altimétrie permettra en outre un suivi en temps réel des champs de vagues et en facilitera la prévision.

La cryosphère est l'autre composante du système climatique qui possède une mémoire à long terme et est donc susceptible de jouer un rôle majeur sur les variations climatiques. L'observation des vastes calottes du Groenland et de l'Antarctique présente beaucoup de similitudes avec l'observation de l'océan global. C'est un problème d'observation à grande échelle avec des mesures de grande précision à répéter systématiquement. Ici également, l'altimétrie apparaît comme la seule méthode disponible, capable de déterminer, avec la précision requise, la croissance ou la diminution du volume des calottes, la vitesse à laquelle elles ajustent leur masse et, plus généralement, les mécanismes qui gouvernent leur évolution dynamique. Comme pour l'océan, la connaissance du comportement de la cryosphère est essentielle pour la prévision de l'évolution du système climatique.

Le document qui suit essaye d'expliciter les bases scientifiques et techniques des systèmes de mesure altimétrique adaptés aux problèmes posés. Ces systèmes sont parmi les systèmes de mesures les plus complexes et les plus réussis jamais mis au point. La mesure altimétrique repose en effet sur plusieurs instruments qui ne peuvent fonctionner, avec toute la précision requise, que sur des plates-formes adaptées.

Des efforts considérables ont déjà été réalisés pour exploiter les mesures existantes et préparer les missions altimétriques futures. Ce document constitue une réflexion sur le rôle central et essentiel que les mesures altimétriques joueront sur la réduction de l'énorme incertitude qui existe actuellement sur le futur de notre climat.

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The ocean circulation and polar ice sheet volumes provide important memory and control functions in the global climate. Their long-term variations are unknown and need to be understood before meaningful appraisals of climate change can be made. Satellite altimetry is the only method for providing global information on the ocean circulation and ice sheet volume. Two decades of research and development and three flight programs have demonstrated the capabilities of altimeters. In the coming decade, a robust altimeter measurement program is planned which will initiate global observations of the ocean circulation and polar ice sheets. In order to provide useful information about the climate, these measurements must be continued with unbroken coverage into the next century.

Space agencies in the United States, Europe, Japan, and other countries are charged with developing programs that will provide meaningful understanding of global change issues, especially the role of the ocean in the climate system. In this report, an international science working group has summarized the past results, outlined the near-term goals, and, most importantly, presented requirements and options for future altimeter missions. These recommendations are intended for agencies involved in the development of satellite programs. The intent is to provide the foundation for the planning of altimeter missions that can be used by the international science community for global change research in the late 1990s and beyond.

> **There are three basic scientific objectives for a long-term altimetric program, they are:**
>
> * **Ocean circulation**
> * **Polar ice sheets**
> * **Mean sea-level change**

In order to provide useful information on these objectives for climate research, uninterrupted continuous measurements extending for several decades are required. The funded altimeter missions (TOPEX/Poseidon, ERS-1, and ERS-2) have been planned to operate only through 1997.

> **The primary recommendation of this report is for a succession of high-accuracy satellite altimeter systems designed for ocean and ice observations, beginning in 1997 at the latest, to establish an uninterrupted time series over the global ocean and major ice sheets for at least the subsequent 20 years.**

The accuracy of an altimeter measurement system is critically dependent on many factors other than the accuracy of the altimeter instrument itself; including the configuration of the orbit, the precision of the orbit determination, and coincident atmospheric and ionospheric refraction measurements. Unlike many other satellite instruments, the effective deployment of an altimeter is not a simple matter of being added to the payload of any platform of opportunity. There is a clear consensus among the research community that:

> The greatest scientific benefit will be achieved with a series of dedicated high-precision altimeter spacecraft, for which the choice of orbit parameters and system accuracy are unencumbered by requirements of companion instruments.

It is recognized that the equitable distribution of resources will likely require some compromise, whereby a precision altimetric system would share a platform with a limited number of compatible sensors. This is a preferred alternative to altimeter deployment on very large, multi-instrumented platforms for which required orbit control and radial accuracy cannot be achieved. We note that several technical improvements to altimeter measurement systems will reduce weight, power, and ultimately, cost of future altimeter systems and increase the flexibility of mission design parameters.

We summarize in this section a concise set of recommendations regarding key issues. The more lengthy background material follows in a series of chapters which build the scientific rationale and give more detailed review of the technical aspects.

General Requirements

Sampling Strategy

To ensure a continuous time series, and to improve oceanographic sampling, a program of multiple contemporaneous radar altimeters is strongly urged.

Coordination

Several agencies will likely contribute to an altimetric program requiring multiple long-term missions. It is essential that the different missions be coordinated and optimized through an international scientific working group so as to satisfy the main objectives listed in this report. It is also highly desirable that a standard altimeter design should be adopted or at least that great care should be taken in instrument design and test procedures to ensure intercompatibility of results over all types of terrestrial surfaces at the desired levels of precision and accuracy.

Accuracy

The overall system accuracy and precision of altimetric measurements must meet TOPEX/Poseidon specifications and should evolve toward sub-decimeter and centimeter levels, respectively.

Important Ancillary Measurements

Gravity Mission

Precise knowledge of the gravity field and the geoid impacts several key issues in satellite altimetry. A dedicated geopotential research satellite would greatly improve estimates of the mean ocean circulation and precision orbit determination. We strongly recommend that the ARISTOTELES mission or equivalent be approved for the earliest possible launch.

Laser Altimeter

A laser altimeter system is needed to accurately measure the changing volume of the polar ice sheets, particularly over the steeper ice sheet margins where radar altimetry has serious limitations. We strongly recommend the Geodynamics Laser Ranging System–Altimeter (GLRS-A) or equivalent be flown, not necessarily on the same platform as a radar altimeter.

Surface Wind Measurements

The maximum scientific benefit of altimetric observations of the ocean circulation can only be attained when they are

carried out contemporaneously with global measurements of the wind field over the ocean surface. This combination of measurements is required to improve our understanding of the coupling between the ocean and atmosphere. We strongly endorse satellite scatterometer missions to measure the global winds over the ocean surface.

Mission Constraints for Satellite Altimetry

Choice of Orbits

The orbit inclinations for future altimeter missions should extend to at least 66° for ocean observations and 82° latitude to cover most of the polar ice sheets. The choice of a Sun-synchronous orbit is acceptable but not preferred for ocean observations because of the way the measurement is confused by the presence of the solar tides. For the purpose of building long time series of observations, successive high-accuracy missions should repeat the same ground tracks. Consideration should also be given to the flight of an instrument in a 90° inclination orbit to provide coverage of all of Antarctica.

Repeat Orbit

Given our inadequate knowledge of the geoid, an exact repeat orbit is necessary so that cross-track geoid gradients do not induce significant errors to the apparent sea-level variability. We recommend that the constraint on orbits to repeat within ±1 km be maintained.

Sampling Rate

Repeat period sample rates between 10 to 20 days have been justified with past studies as being a suitable compromise for ocean circulation observations based on a single altimeter. Definition studies are needed to analyze the sampling strategies for multiple altimeters.

Altimeter System Components

Radar Altimeter Systems

We strongly recommend the evolution of precise, low power, compact, and lightweight altimeter systems in order to create opportunities for smaller satellites with commensurate significant saving in launch costs.

Precise Orbit Determination

There are four candidate precise tracking systems for future altimetric missions: Global Positioning System (GPS); Satellite Laser Ranging (SLR); Precise Range and Range-rate Experiment (PRARE); and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). These should be compared and evaluated during the TOPEX/Poseidon and ERS missions. All future altimeters should incorporate a laser retroreflector ring on the altimeter antenna to provide: redundancy in tracking in case of failure in the space segment of the primary tracking system; altimeter bias calibration and monitoring; and ties into the terrestrial reference frame. We recommend that a codeless GPS receiver be developed to accommodate the possible implementation of anti-spoofing. However, Federal agencies should encourage the U.S. Department of Defense to turn off anti-spoofing and selective availability measures during peacetime to permit the unclassified community full access to the GPS. A differential micro-accelerometer can precisely measure the non-gravitational forces on the spacecraft. It is recommended that the value of such onboard measurements on precise orbit determination be studied.

Reference System

Independent of the chosen orbit determination method, it is indispensable that all tracking networks be linked to a precisely controlled International Earth Reference System (IERS). This system is based on Satellite

Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) station positions, which change in time because of tectonic motions. We strongly recommend that SLR and VLBI operations be continued.

Ionospheric Corrections

The dual-frequency radar altimeter is required for ionospheric corrections. However, alternative approaches have been proposed which may provide equivalent accuracy at reduced overall mission cost. These would be based on DORIS, PRARE, GPS or ionosonde measurements. Such options must be fully evaluated and compared with the measurements from the dual-frequency TOPEX altimeter before a standard approach is adopted for the long term.

Wet Troposphere Radiometer

Three-channel microwave radiometer measurements coincident with the radar altimeter signals are required for correcting the range delay effects of atmospheric moisture and identifying radar returns that are contaminated by rainfall.

Validation

A number of ground-based validation stations must be maintained in order to verify the measurements from all altimeter missions and to cross-validate measurements from different missions.

La circulation océanique et les calottes polaires sont des éléments majeurs de notre système climatique. Ils jouent un rôle important de "mémoire" et de contrôle du climat. Cependant, leurs variations à long terme sont quasiment inconnues et il nous est indispensable de les comprendre afin de pouvoir appréhender correctement la nature des changements climatiques. L'altimétrie spatiale est la seule méthode fournissant une vue globale de la circulation océanique et des calottes. Deux décennies de recherches et de développements et trois missions satellitaires ont mis en évidence le potentiel de cette technique. Dans les années 1990, un programme étoffé de mesures altimétriques est prévu. Il permettra d'initialiser un suivi global et systématique de la circulation océanique et des calottes polaires. Afin de fournir des informations climatiques utiles, il est indispensable que ces mesures soient poursuivies, sans interruption, jusqu'au siècle prochain.

Les agences spatiales des Etats-Unis, d'Europe, du Japon et d'autre pays ont pour tâche de développer des programmes d'observation permettant de mieux comprendre les variations du climat, et en particulier le rôle de l'océan dans le système climatique. Dans ce rapport, un groupe international de scientifiques résume les résultats acquis grâce à l'altimétrie, souligne les objectifs à court terme et, surtout, détaille les exigences auxquelles les missions altimétriques futures doivent satisfaire tout en indiquant les options possibles. Le relevé de ces exigences est destiné aux agences impliquées dans le développement de programmes spatiaux. Le but est de leur fournir les bases nécessaires pour planifier les missions altimétriques futures dont les données pourront être utilisées, dès la fin des années 90, par la communauté scientifique impliquée dans la recherche sur les changements globaux.

> Trois objectifs scientifiques fondamentaux justifient la mise en place d'un programme à long terme d'altimétrie satellitaire. Ce sont :
> * La circulation océanique
> * Les calottes polaires
> * Les variations du niveau moyen des mers.

Afin d'obtenir des informations utiles pour la recherche climatique dans ces trois domaines, il est essentiel de disposer de mesures ininterrompues durant plusieurs décennies. Les missions altimétriques financées (TOPEX/Poseidon, ERS-1, ERS-2) sont prévues pour durer jusqu'en 1997 seulement.

> Notre recommandation principale est de mettre en place une succession de systèmes altimétriques satellitaires de grande précision conçus pour observer les océans et la cryosphère. Les première missions sont à prévoir dès 1997 et doivent s'étendre, sans interruption sur, au moins, une vingtaine d'années.

La précision d'un système de mesure altimétrique dépend de façon critique de plusieurs facteurs autres que la précision de

l'altimètre lui-même. Parmi ceux-ci, on peut citer le type d'orbite choisi, la précision de la détermination de l'orbite et la mesure des erreurs liées à la propagation du signal à travers l'ionosphère et la troposphère. Contrairement à de nombreux autres systèmes embarqués, un altimètre ne peut pas être mis en oeuvre de façon efficace sur n'importe quel type de plate-forme. Il existe donc un large consensus au sein de la communauté scientifique pour affirmer que:

> **On tirera le plus grand profit scientifique d'une série de missions altimétriques dédiées de haute précision pour lesquelles le choix des paramètres d'orbite et la précision du système de mesure ne seront pas entravés par les exigences d'autres systèmes embarqués.**

Il est néanmoins reconnu qu'une distribution équitable des ressources peut requérir un compromis par lequel une mission altimétrique précise aurait à partager une plate-forme avec un nombre limité d' instruments compatibles. Ce type de solution est préférable à un déploiement sur une plate-forme multi-missions de grande taille sur laquelle le contrôle et la détermination précise de l'orbite sont sérieusement compromis. On note également que divers progrès techniques dans le domaine de la mesure altimétrique tendent à réduire le poids, la puissance consommée et finalement le coût des systèmes futurs. Ces améliorations pourraient amener plus de flexibilité dans la conception des missions futures.

On regroupe dans ce synopsis un ensemble limité de recommandations portant sur des points essentiels. Un exposé plus détaillé est présenté dans les chapitres suivants. On y détaille les bases scientifiques et techniques de l'altimétrie.

Exigences de base

Stratégie d'échantillonnage

Afin d'assurer la continuité et d'améliorer la qualité de l'échantillonnage des phénomènes océaniques, nous recommandons, de façon urgente, la mise en place d'un programme comportant plusieurs altimètres en vol simultanément.

Coordination

Plusieurs agences spatiales sont susceptibles de participer à un programme altimétrique de longue haleine requérant plusieurs missions simultanées. Il est essentiel que ces différentes missions soient coordonnées et optimisées par un groupe international de scientifiques de façon à s'assurer que les recommandations principales figurant dans ce rapport soient satisfaites. Il est également hautement désirable qu'une conception de base standard soit adoptée pour les altimètres ou, du moins, que le plus grand soin soit pris lors de la conception des différents instruments afin que leurs résultats soient comparables, sur tout type de surface, avec la précision et l'exactitude requises.

Exactitude

L'exactitude et la précision des systèmes altimétriques complets doivent satisfaire les spécifications de TOPEX/ Poseidon et devraient tendre vers des valeurs, respectivement, sub-décimétriques et centimétriques.

Mesures Auxiliaires Importantes

Mission Gravimétrique

Notre connaissance du champ de gravité terrestre et du géoïde affecte divers aspects fondamentaux de l'altimétrie spatiale. Un satellite dédié à l'étude du géopotentiel permettrait d'améliorer très

sensiblement la précision des orbites calculées et notre estimation de la circulation océanique moyenne. Nous recommandons donc vivement que la mission ARISTOTELES, ou une mission équivalente, soit approuvée pour un lancement aussi rapide que possible.

Altimétrie Laser

Un système d'altimètre laser est nécessaire pour mesurer précisément les variations de volume des calottes polaires, en particulier en présence de pentes très prononcées où la mesure radar pose problème. Nous recommandons fortement que le "Geodynamics Laser Ranging - Altimeter (GLRS-A)", ou un instrument équivalent soit embarqué, pas nécessairement sur la même plate-forme qu'un altimètre radar.

Mesure des vents de surface

On ne tirera un profit scientifique maximum d'observations altimétriques de la circulation océanique que si celles-ci sont couplées à des mesures globales du champ de vent à la surface des océans. Cette combinaison de mesures est requise pour améliorer notre compréhension du système couplé océan-atmosphère. Nous soutenons fortement toute mission de diffusiométrie consacrée à la mesure des vents de surface sur océan.

Contraintes liées à la mission d'un satellite altimétrique

Choix d'orbite

L'inclinaison des orbites des missions altimétriques futures doit atteindre au moins 66° pour l'observation des océans et 82° pour l'observation des calottes polaires. Pour l'observation des océans, le choix d'une orbite héliosynchrone est acceptable, sans être préféré à cause d'un effet stroboscopique des marées solaires. Afin de bâtir de longues séries temporelles de mesures, il serait préférable que les missions d'altimétrie précise se succèdent en gardant les mêmes traces au sol. On devrait aussi prendre en considération une mission ayant une orbite inclinée à 90° pour couvrir tout le continent Antarctique.

Répétitivité de l'orbite

Compte tenu de notre connaissance actuellement inadéquate du géoïde, il est nécessaire de maintenir une orbite exactement répétitive de façon à ce que les gradients de géoïde perpendiculaires à la trace n'induisent pas d'erreur significative sur la variabilité océanique mesurée. Pour ce faire, nous recommandons que la contrainte de répétitivité sur l'orbite soit maintenue à ± 1 km.

Echantillonnage

Des périodes de répétitivité comprises entre 10 et 20 jours constituent un compromis acceptable pour l'observation de la circulation océanique à l'aide d'un seul altimètre. Nous recommandons que de nouvelles études soient menées pour définir les stratégies d'échantillonnage adaptées à plusieurs altimètres volant simultanément.

Composantes d'un système altimétrique

Systèmes d'altimétrie radar

Nous recommandons fortement que soit favorisée l'évolution de systèmes de mesure altimétrique qui soient précis, compacts, légers et économes en énergie afin de se ménager des possibilités d'emport sur de petits satellites, dont les coûts de lancement sont sensiblement réduits.

Détermination précise de l'orbite

Quatre systèmes de poursuite précise peuvent être envisagés pour les missions altimétriques futures : GPS (Global Positioning System), le positionnement laser (Satellite

Laser Ranging - SLR); PRARE (Precise Range and Range-rate Experiment) et DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite). Ces systèmes seront comparés et évalués lors des missions TOPEX/Poseidon et ERS. Toutes les missions altimétriques futures devraient comprendre un anneau de réflecteurs laser autour de l'antenne de l'altimètre afin d'assurer la redondance du système de poursuite en cas de panne du segment bord du système nominal, la calibration et le suivi du biais de l'altimètre et le rattachement à un système de référence terrestre. Nous recommandons qu'un récepteur GPS "sans code" soit développé afin de maintenir une précision d'orbite sub-décimétrique en cas de mise en service d'un système militaire de protection de la mesure. Néanmoins, toutes les parties intéressées devraient inciter le Ministère de la Défense Américain à ne pas brouiller ni coder les mesures GPS en période de paix afin que les utilisateurs civils puissent y avoir accès. D'autre part, un micro-accéléromètre différentiel est un instrument capable de mesurer les forces non-gravitationnelles agissant sur le satellite. Nous recommandons que l'impact de telles mesures sur le calcul d'orbites précises soit étudié.

Système de référence

Indépendamment de la méthode choisie pour déterminer l'orbite, il est indispensable que tous les réseaux de poursuite soient rattachés à IERS (International Earth Reference System), un système de référence précisément contrôlé. Ce système s'appuie sur le réseau de poursuite laser SLR et sur les positions de stations déterminées par interférométrie à très longue base (VLBI). Ces positions changent à cause des mouvements tectoniques, nous recommandons donc fortement que l'opérationnalité des systèmes SLR et VLBI soit maintenue.

Correction ionosphérique

Actuellement, l'altimètre radar bifréquence reste la solution de principe à utiliser pour obtenir la correction ionosphérique avec l'exactitude requise. Cependant des solutions alternatives ont été proposées. Elles pourraient fournir une mesure de qualité équivalente à un moindre coût. Ces solutions sont basées sur l'utilisation de mesures de sondes ionosphériques, de DORIS, PRARE ou GPS. De telles solutions doivent être soigneusement évaluées. Leurs résultats doivent être comparés avec ceux de l'altimètre bifréquence TOPEX avant que l'on n'adopte une stratégie standard pour le long terme.

Radiomètre pour la correction de troposphère humide

Pour déterminer cette correction avec la précision requise il faut utiliser un radiomètre micro-onde trifréquence dont les mesures coïncident avec les mesures altimétriques. Cet instrument permet également d'identifier les mesures contaminées par la présence de pluie.

Validation

Quelques stations de validation doivent être maintenues afin de vérifier les mesures de l'ensemble des missions altimétriques et d'intercalibrer les mesures des différentes missions.

ALTIMETER-RELATED SPACECRAFT: 1970-2020

1970	1980	1990	2000	2010	2020

NASA Geos-3 ▨▨▨

NASA Seasat ▨

USN Geosat ▨▨▨▨

ESA ERS-1 ⬜➡

US/French TOPEX/POSEIDON ⬜➡

ESA ERS-2 ⬜➡

USN GEOSAT Follow-on ▽ ▽ ▽ ▨➡

ESA POEM ▽ ▨➡

TOPEX Follow-on ▨➡

NASA EOS Alt ▽ ▨➡

▨▨▨ Completed Mission

⬜ Supported (In space or under construction)

▨ Tentative (Proposed or in early stages of development)

Mission	Dates	Agency	Repeat Orbit	Corrections	System Acc. (cm)
Geos-3	1975-1978	NASA	No	None	100
Seasat	1978	NASA	Partial	WV	50
Geosat	1985-1989	U.S. Navy	17 days-11/86-11/89	None	50
ERS-1	1991	ESA	3,35,176 days	WV	25
TOPEX/ Poseidon	1992	NASA/ CNES	10 days	WV, Iono	13
ERS-2	1994	ESA	3,35 days	WV	20
GFO	1995	U.S. Navy	17 days	WV	TBD
POEM	1998+	ESA	35 days	WV, Iono	TBD
TOPEX Follow-on	1998+	NASA/ CNES	TBD	WV, Iono	TBD
EOS Alt	2003+	NASA	TBD	WV, Iono	TBD

Range Corrections refer to direct measurements from the spacecraft; coincident with the radar signal:
WV-Total columnar water vapor range delay
Iono-Total ionospheric range delay

System Accuracy refers to the available performance for past missions and specified performance for future missions. The largest part of the uncertainty comes from the radial orbit error, which can be filtered out and reduced for most applications. For example, after removal of this error the overall uncertainty for TOPEX/Poseidon is expected to be below 5 cm rms.

1. INTRODUCTION

The climatological expression of the projected global warming is widely expected to become detectable during the next two decades. The ability to forecast climate change is a central goal of the international Global Change Research Program (GCRP). Such capability is impossible without measurements of the physical properties of the Earth's climate system. The climate system consists of five basic components: the atmosphere, ocean, cryosphere, biosphere, and geosphere. The ocean and cryosphere are significant elements. They are the major reservoirs of heat and water, thereby providing the memory and control of the climate. For example, the ocean, which transports one third to one half of the heat from tropical regions towards the poles, moderates the climate at higher latitudes. The cryosphere, which stores about 80% of the available fresh water in the Greenland and Antarctic ice sheets, regulates the hydrologic cycle and sea-level. Satellite altimeters provide fundamental information about the ocean circulation and surface elevation of the ice sheets that cannot be obtained by any other means. This report describes the scientific objectives and requirements for satellite altimeter measurements of the ocean and cryosphere in global change research. Recommendations are presented for carrying out altimeter missions over the coming decades in order to meet these goals.

The ocean circulation and its fluxes of heat, moisture and biochemical properties are fundamental influences on climate. They are among the highest research priorities of the GCRP. Because the circulation and its variability are manifested in the sea surface topography, satellite altimetry provides a means to measure the circulation and describe its changes. No other instrument system permits observation of the global ocean circulation.

Since the ocean by itself plays an important role in the Earth climate system with time scales by far exceeding those of the atmosphere, it is mandatory to globally observe the ocean flow field and monitor its property fluxes. Any changes in the large-scale thermohaline and wind-driven circulation or in the eddy field will directly affect the climate. Therefore, long-term weather forecasting and climate predictability will benefit from the use of altimeter systems in conjunction with numerical ocean circulation models.

The ocean circulation is driven by fluxes of momentum, heat, and water between the ocean and the atmosphere. These fluxes are not known with sufficient accuracy for the purpose of climate modeling. Global observations of the surface winds over the ocean from satellite scatterometers coupled with altimeter measurements of the circulation have the potential for providing a dramatic increase in our understanding and prediction capability of the ocean circulation at scales that are important for global change research.

The mass balance of the vast ice sheets of Greenland and Antarctica is unknown. Over a century of field observations have been incapable of describing this important element of the climate system. The major components of mass balance that can poten-

tially be measured from space include snow accumulation, surface melting, ice motion, and ice volume. Satellite altimetry can provide a global measure of changes in ice sheet elevation, a direct indication of volume change. Satellite altimetry also has the potential to measure the mean level of the sea. These measurements could significantly improve our understanding of the hydrologic cycle in global climate.

Over the past two decades through the Geos-3, Seasat, and Geosat missions, satellite altimetry has demonstrated its potential to revolutionize the study of the circulation of the oceans and the mapping of the polar ice sheets. These successes have come through the fruitful collaborations among engineers and scientists from many nations working in concert with the National Aeronautics and Space Administration (NASA), United States Navy (USN), Centre National d'Etude Spatiale (CNES), and European Space Agency (ESA) to develop advanced techniques, both in sensor development and scientific analysis. The result is that satellite radar altimetry has become a technically mature tool for globally mapping the ocean circulation and its variability, for observing the changes in elevation of the polar ice sheets, and for monitoring the mean level of the ocean.

Beginning with the July 1991 launch of the ESA ERS-1 mission, followed a year later by the joint NASA/CNES TOPEX/Poseidon mission and 3 years later by ERS-2, existing programs could provide overlapping altimetry missions through about 1997. In addition, the USN is planning a 10-year Geosat Follow-On (GFO) program consisting of a series of inexpensive altimeter satellites to be launched as early as 1995.

Beyond 1997, agency plans for altimeters are tentative. ESA is developing an altimeter system capable of tracking ocean, ice, and land surfaces (RA-2) for launch around 1998 on the Polar Orbit Earth observation Mission (POEM-1). NASA is considering a series of altimeters for its Mission To Planet Earth (MTPE), including a follow-on to TOPEX later in this decade.

The TOPEX/Poseidon mission (1992-1995, possibly extended to 1997) will be the most accurate altimetric system developed to date. It is a major element of the World Ocean Circulation Experiment (WOCE), a program designed to determine the general ocean circulation over a period of 3 to 5 years. TOPEX/Poseidon is the only altimetric mission specifically designed for the purpose of studying the ocean circulation. It sets the performance standard for future altimetric missions for climate research.

Continuity of measurements over many decades is essential to detect climate change and to understand its elements. Though several altimetry missions are planned in the future, it should not be concluded that adequate coverage will be available over the next decade and beyond, for the following reasons :

• All missions to follow TOPEX/Poseidon are only in the proposal stage or early phases of development.

• Not all altimetric missions have the technical capability or continuity to make them suitable for meeting the scientific requirements for global change research.

• Some mission characteristics may be incompatible with the scientific requirements for climate change research. The extent to which compromises on these characteristics can be made is a complex question that must be addressed case by case.
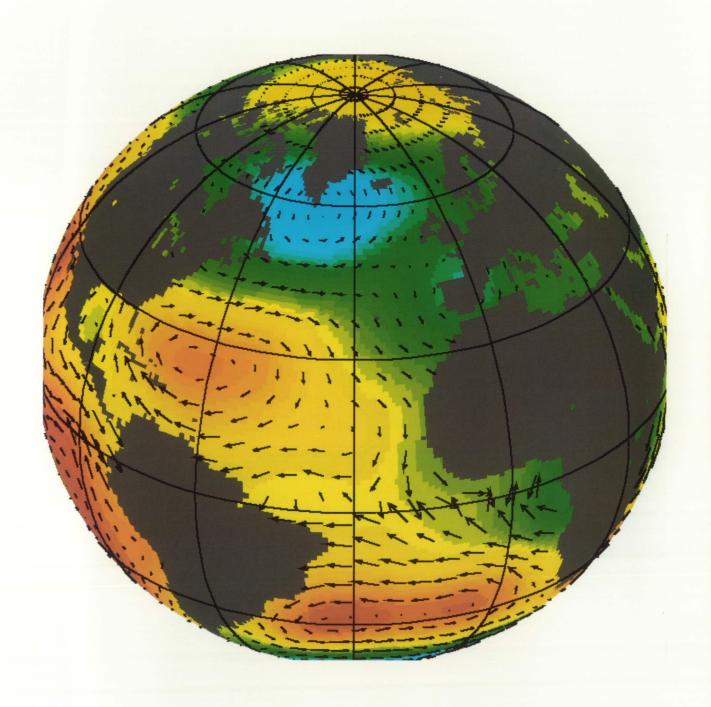
For example, the GFO mission provides a scientifically useful companion to TOPEX/Poseidon but it does not meet the same precision specifications. The POEM and MTPE altimeters are planned following TOPEX/Poseidon specifications, but in some

cases have been proposed to share space on large platforms with several other types of sensors. Such sensors have competing requirements and necessarily degrade the overall mission capability. Therefore, including altimeters on very large, multi-instrumented platforms may not be capable of providing data of the quality necessary for studying the large-scale ocean circulation or the ice sheets.

Governmental agencies are now in the process of choosing payload and satellite configurations for many of these missions, including some not scheduled for launch until far in the future. Once such choices are made, there is normally an inflexibility in accommodating further developments, either technical or scientific. Therefore, a central question addressed by this report is whether the scientific objectives and requirements for the global change research program concerning ocean circulation and the mass balance of the ice sheets can be met by the altimeter systems now being considered.

This report presents a review of the ocean and cryosphere climate research objectives that can be achieved with altimetry and their requirements. This is followed by an analysis of the technical capabilities and alternatives for meeting these requirements. Mission design options are summarized, and recommendations are suggested for an optimal satellite altimeter program for global change research. The intent is to provide the sponsoring agencies with scientific and technical guidance so that appropriate decisions about altimetry can be made to further understanding of global change and its implications.

An estimate of the large-scale global surface topography and circulation of the ocean relative to the geoid based on 2 years of Geosat altimeter measurements. (Figure courtesy of C. J. Koblinsky, NASA/GSFC.)

2. SCIENTIFIC OBJECTIVES

Satellite altimetry has come to be the central, instrumental focus of mesoscale to global-scale oceanography and polar ice sheet studies. It is of intense interest in both for a single, central reason: the precise and accurate measurement of the shape of the sea surface and of the polar ice caps is the only physical variable measurable from space that is directly and simply connected to the large-scale movement of water, the ice sheet volume, and the total mass and volume of the ocean. The ocean circulation and ice sheet volume are two dominant elements of the climate system. They are simultaneously both causes of and indicators of climate change. In this context, there are three major scientific objectives for a long-term satellite altimeter program; they are:

• Measure the mean and variable global ocean circulation;

• Monitor the polar ice sheet volume; and

• Observe the global mean sea-level change.

2.1. Ocean Circulation

The ocean is a global fluid, with global consequences (climate), as well as regional ones (weather, fisheries, military and commercial operations, etc.). None of these consequences can be properly understood without being able to observe the system as a whole. Thus, if one suspects that the climate is changing in part because of alterations in the ocean heat transport, no regional program can possibly observe such variations. In addition, the movement of chemical and biological fields by the circula-

tion is, itself, a vital element of the climate system because of their central role in the control of atmospheric carbon concentrations. Fisheries, pollutants, etc. are believed to be governed by the movement of water on at least ocean-basin scales.

The length and time scales of these processes are too large for conventional oceanographic instrumentation. Even regions of comparatively modest size, a few hundred kilometers across, cannot be adequately measured by shipborne or moored instruments because of attendant costs and limited endurance. Satellite altimetry is the only known method by which oceanographers can observe, and thereby come to understand and eventually predict the ocean circulation, its fluctuations, and its property fluxes on the global scale.

Principle of Altimetric Measurements

The fundamental altimetric concept for measuring the ocean circulation is simple. Movement of water in the sea on spatial scales exceeding about 30 km and persisting and evolving on times exceeding about 1 day is strongly affected by the Earth's rotation (the Coriolis forces). These effects are manifested by deflections of the sea surface associated with the strength and direction of the flows. So for example, in the Northern Hemisphere, the sea surface elevation increases to the right of the flows (to the left in the Southern Hemisphere). The phenomenon is identical to that familiar in weather patterns—the flows being principally around the highs and lows of sea surface elevation.

Given the strengths of the deflections of the sea surface, one can infer the magnitudes and directions of the oceanic water movements, and their subsequent evolution.
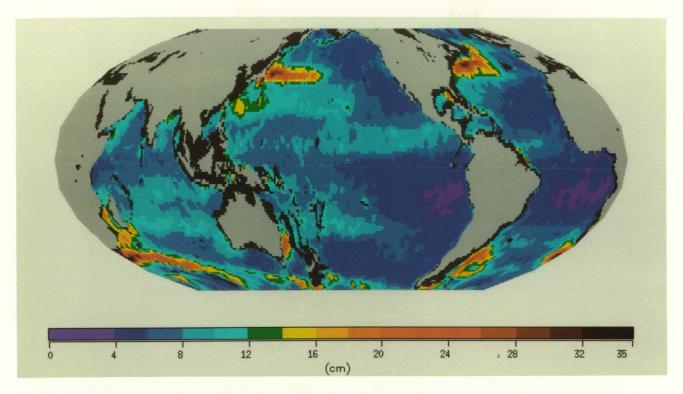
Unlike all other measurements made from space, the sea surface elevations reflect more than just surface conditions. Simple physical arguments show that surface flows inferred from surface elevations cannot change significantly as one penetrates into the oceanic depths, until one has moved a distance in the vertical given by $z \sim fL/N$, where f is the Coriolis parameter, L is the horizontal distance over which the surface currents change, and N is a measure of the oceanic stratification (the buoyancy frequency). Thus, a surface elevation change measured by an altimeter which changes significantly over 500 km reflects oceanic currents to depths of roughly 500 to 1000 m.

Past Achievements

Past altimetric missions (Geos-3, Seasat, Geosat) were not designed for the purpose of understanding global change. However, these missions with their high noise levels and sub-optimum designs have been subjected to intense scrutiny. The data have been analyzed by a large number of scientists intent upon extracting useful information from them. The results of this multitude of studies (see Wunsch and Gaposhkin, 1980; Cheney and Marsh, 1981; or the reviews by Brown and Cheney, 1983; Douglas et al., 1987; Chelton, 1992; and the edited collections of articles by Bernstein, 1982; Kirwan et al., 1983; and Douglas and Cheney, 1990) show that altimetry is quantitatively useful for a wide variety of research, including: determining the absolute circulation (Tapley et al., 1988; Marsh et al., 1990; Nerem et al., 1990); the variations of the circulation on the very largest spatial scales (Miller et al., 1988; Chelton et al., 1990; Wunsch, 1991); the global mapping of eddy

Typical Sea-level Variations

Phenomena	Vertical Range (cm)	Spatial Scale (km)	Time Period (days)
Ocean Gyres			
— Mean	100	>1000	
— Variations	10	>1000	>300
Mesoscale Eddies	25	~50	>30
Western Boundary Currents			
— Mean	100	100	
— Meanders, Variations	100	100	>10
Eastern Boundary Currents			
— Mean	20	500	
— Meanders, Variations	10	500	>10
Equatorial Currents			
— Mean	20	>500	
— Meanders, Variations	10	>500	>50
El Niño Response of Equatorial Sea-level	20	>500	~1000

The global distribution of the standard deviation of sea surface variations, reflecting the eddy kinetic energy, based on 2 years of Geosat altimeter data. (Figure courtesy of C. J. Koblinsky, NASA/GSFC.)
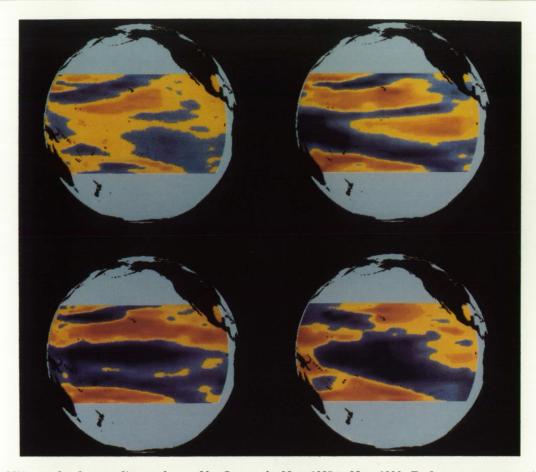
energies (Cheney et al., 1983; Sandwell and Zhang, 1989; Zlotnicki et al., 1989; Le Traon et al., 1990; Le Traon, 1991; De Mey and Menard, 1989); measuring fluctuations in the great current systems (Chelton et al., 1990; Zlotnicki, 1991; Kelly and Gille, 1990); and improving ocean predictability through the assimilation of altimeter data in numerical models (De Mey and Robinson, 1987; Robinson and Walstad, 1987; Malanotte-Rizzoli and Holland; 1989; Verron, 1990; Verron, 1992; Haines, 1991b).

This early work has primarily demonstrated that satellite altimeters are a very effective tool for detection of transient sea-level features associated with the ocean mesoscale eddies (Cheney et al., 1983). The kinetic energy of the ocean circulation is dominated by the mesoscale eddy field virtually everywhere. These eddies have two important consequences for measuring and understanding the ocean circulation. In some regions, they are known to contribute sig-

nificantly to the oceanic fluxes of momentum, heat, and other properties. In all regions, their presence places severe demands upon the sampling of the larger scale, more sluggish circulation, so as to avoid aliasing of the mesoscale into a fictitious description of the general circulation.

Conventional hydrographic measurements from ships provided some indications that the space/time characteristics of the eddy field are not homogeneous. In principle, conventional instrumentation is not able to systematically study eddy characteristics over long distances and periods.
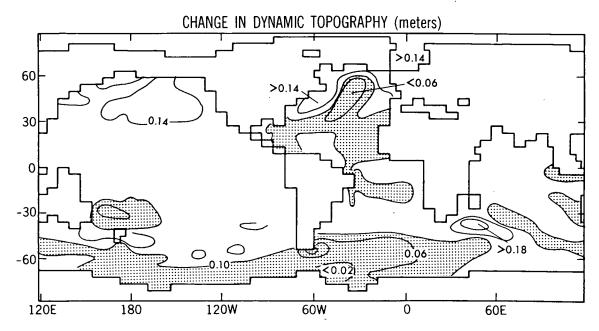
Mesoscale eddies have a horizontal scale of about 25 to 500 km and move across the ocean at speeds of generally less than 10 km/day. The combination of size and speed make them easily observable by satellite altimeters as an anomaly from mean sea-level. The largest eddies, which are normally formed at western boundary currents, seem

El Niño/La Niña sea-level anomalies as observed by Geosat, for Nov. 1985 to Nov. 1989. Each map represents a 1-year mean relative to period, April 1985 - April 1986. Dark blues indicate lows less than -15 cm; dark oranges indicate highs greater than 15 cm. The sequence of changes in the four maps can be summarized as follows: 1986 (upper left) —Normal sea-level 1 year prior to El Niño; 1987 (upper right) —El Niño. Relaxation of the trade winds, which normally blow strongly towards the west, has caused water to shift from the west to the east along the equator. Sea-level north of 10°N is anomalously high, the result of water being displaced from the equatorial region; 1988 (lower left) —The tropical Pacific has now switched from El Niño to La Niña conditions. Stronger-than-normal trade winds cause intense upwelling (and therefore lower sea-level) in the central Pacific. Positive anomalies in the north and south remain for a second year; 1989 (lower right) —La Niña persists in the central Pacific, but elsewhere the ocean is beginning to return to normal. Positive anomalies in the north have started to break up. The far western Pacific has recovered the water lost during El Niño and, in fact, has higher levels than in 1985-86. (Figure courtesy of L. Miller, NOAA/NOS.)

to be important to thermohaline fluxes, and to the larger scale climate system as they transfer ocean properties from one regime to another. For example, using a combination of Geosat altimeter and conventional hydrographic measurements, Gordon and Haxby (1990) observed eddies from the Agulhas Retroflection region carrying Indian Ocean water into the South Atlantic. The continual monitoring by satellite altimeters of mesoscale activity in the ocean is required for the study of ocean current stability and thermohaline fluxes and, as such, is an important contribution to global climate studies.

At larger scales, the greatest success from the early altimeters has been the ability to monitor changes in tropical sea-level. The transport of warm surface water into and out of the equatorial Pacific is thought to play an important role in regulating the El Niño-Southern Oscillation (ENSO). Although many processes are involved in these interannual coupled atmosphere/ocean phenomena, one important indicator of the condition in the tropics appears to be the volume of upper layer water near the equator. Analyses of Pacific island tide gauge data (Wyrtki, 1979; Wyrtki, 1985) have helped

CHANGE IN DYNAMIC TOPOGRAPHY (meters)

The global pattern of projected dynamic height (0-1100 decibar) changes from the present to a future climate, based on a simulation of the transient coupled ocean-atmosphere response to a doubling of atmospheric carbon dioxide, assuming the IPCC scenario of 1% per year CO_2 increase (Manabe, et al., 1991). The contour interval is 0.04 meter. Shading indicates regions having less than the global mean sea-level rise of ~0.12 meter. (Figure courtesy of K. Bryan, NOAA/GFDL.)

document some aspects of this water transport cycle, but the immense size of the Pacific results in undersampling by this and all other conventional measurement techniques. The long time series of Geosat measurements permitted the first Pacific basin-wide synoptic view of sea-level change during an ENSO event (Miller et al., 1988; Miller and Cheney, 1990). Long-term monitoring of tropical sea-level by satellite altimeters is required for an improved understanding of ENSO dynamics and short-term climate prediction.

Future Directions

Satellite altimetry has become the only known method for oceanographers to observe the global ocean general circulation and its fluctuations. It is this unique ability to provide dynamical boundary conditions upon the flows occupying much of the three-dimensional ocean, globally and continuously, that will make altimetry so useful and powerful a tool for understanding and monitoring the general circulation and global flow changes. The ocean science community is developing large-scale ocean

circulation models capable of being forced by these boundary conditions. No other observational system can provide measurements that will have a similar impact on ocean predictability.

Altimeter measurements provide information about the space/time characteristics of the fluctuating flow field, which is needed to verify numerical eddy resolving ocean circulation models to be used for ocean prediction studies (Stammer and Boening, 1992). This step is vital and has to be done prior to data assimilation studies in order to detect and ease model deficiencies. Therefore, accurate long-term altimeter measurements with high spatial and temporal sampling are needed to increase ocean predictability not only through data assimilation but also by model improvements through model-data intercomparison studies.

The early satellite altimeter missions were able to achieve only a marginal quantitative determination of global-scale mean or variable ocean circulation because of system

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inaccuracies. In all of these missions, a number of analyses (Marsh et al., 1990; Nerem et al., 1992; Wunsch, 1991) have shown that orbit determination errors nearly overwhelm the mean and variable large-scale (> 1000 km) ocean circulation. In addition, uncertainties in the marine geoid at scales less than 2000 km continue to undermine efforts to measure the mean circulation. TOPEX/Poseidon has been designed, but not yet flown, with the understanding of the ocean circulation as the central purpose. The earlier studies have clearly demonstrated that this mission will correct error sources in the previous missions that have masked the large-scale ocean circulation.

The nature of the ocean circulation variations associated with possible future climate change can be assessed with contemporary coupled ocean-atmosphere climate models. For example, Manabe et al. (1991) simulated the transient response to a doubling of atmospheric carbon dioxide using the International Panel on Climate Change (IPCC) (Houghton et al., 1990) "business-as-usual" scenario of 1% per year CO_2 increase. The heating of the ocean was not uniform, and the uneven thermal expansion of the model ocean resulted in widespread regional variations in dynamic topography (sea surface topography) and, hence, ocean

circulation. For example, a high and low dipole was predicted for the North Atlantic associated with a weakening of the thermohaline circulation. The range between the highs and lows of the global pattern is about 16 centimeters. The need to measure this degree of variability underscores the requirement for a long-term altimeter observatory of TOPEX/Poseidon accuracy.

Continuing altimetric measurements of TOPEX/Poseidon quality into the next century are crucial for understanding and predicting changes in the ocean on decadal scales which have a significant influence on the climate.

2.2. Polar Ice Sheets

Changes in ice sheet volume are also connected to climate, both as indicators and as causes of climate change (Folland et al., 1990). There is broad agreement that temperate-latitude mountain glaciers and icefields have decreased in volume during the past century; melting and retreat of these relatively small ice masses are thought to account for a substantial fraction of observed sea-level rise during that time, beyond the fraction attributable to thermal expansion of

Typical Polar Ice Sheet Elevations

Phenomena	Vertical Range (m)	Spatial Scale (km)	Time Period (days)
Antarctic Ice Sheet			
— Mean Profile	4000	5000	
— Seasonal Variation	1	200	~100
— Interannual Variation	0.5	200	~1000
Greenland Ice Sheet			
— Mean Profile	3000	2000	
— Seasonal Variation	2	200	~100
— Interannual Variation	0.5	200	~1000

A 2-m contour map of the Larsen Ice Shelf in 1978 from Seasat altimeter data. (Figure courtesy of J.K. Ridley, Mullard Space Sciences Laboratory, University College, London.)
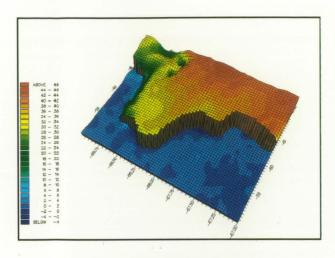
ity is the order of 1 m/year. Altimetry is a unique tool to monitor the mass balance and precisely map the topography of that ice sheet. This directly helps to determine the ice dynamics: the flow depends on snow accumulation rate (which can be estimated from satellite data), ice thickness, bottom rock topography, boundary conditions at the ice sheet periphery and rheological parameters. To the first order, the flow is laminar in the maximum slope direction. Precise maps of the surface ice sheet topography thus allow estimation of the ice thickness, the flow lines and their divergence. Altimetry provides dynamical constraints on the ice flow. It can be used to monitor the evolution of the ice sheets in response to their changing environment.

The West Antarctic ice sheet is thought to be potentially unstable and capable of relatively rapid change, because it is grounded far below sea-level and is discharged, predominantly, by fast-flowing ice streams (National Research Council, 1985). This ice sheet is entirely south of 72°S, except for the Antarctic Peninsula, and thus has not been measured with Geosat and Seasat altimetry. Field studies have shown that major ice streams of the Ross Ice Shelf sector are changing rapidly, and that at least two have negative mass-balances, and are thus contributing to global sea-level rise (Stephenson and Bindschadler, 1988; Shabtaie et al., 1988; Thomas et al., 1988; Whillans and Bindschadler, 1988; Bindschadler and Scambos, 1991). The net mass balance of the entire West Antarctic ice sheet is not yet known, although attempts have been made to evaluate the mass balance of particular drainage basins from sparse field data (Crabtree and Doake, 1982; Shabtaie and Bentley, 1987).

the ocean (Meier, 1984; National Research Council, 1985; Warrick and Oerlemans, 1990). However, this conclusion is based upon extensive extrapolation of mass-balance data from the small number of glaciers that have been studied in detail. Much broader observational coverage is needed. Measurement of these ice masses is, unfortunately, beyond the capability of satellite radar altimeters because of the glaciers' steep slopes, rough topography, and small size. (See Appendix A). However, the vast polar ice sheets of Greenland and Antarctica, whose mass-balance could have a dramatic impact on climate change, are well suited to measurement with satellite radar altimeters.
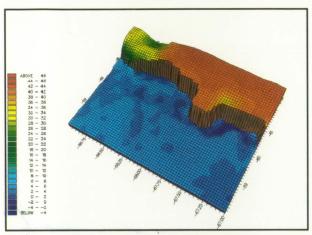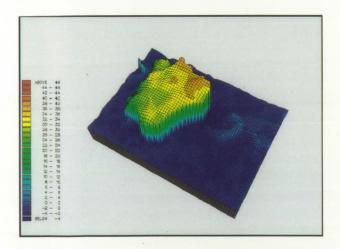
It appears that the immense Antarctic ice sheet has not yet reached equilibrium since the last glacial period as ice flow veloc-
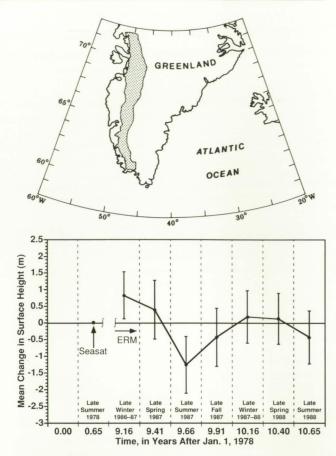
Past altimeters have also been shown to provide a valuable mapping capability over ice shelves, permitting identification of ice stream inflows, grounding lines, and crevassed areas (Partington et al., 1987; Ridley
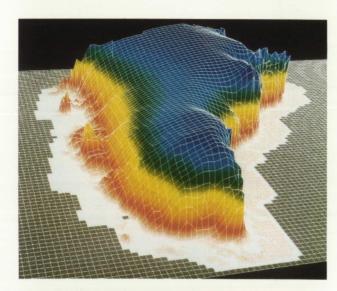
The Larsen Ice Shelf as mapped by the Geosat altimeter during 1985, 1986 before and after the calving of a 1000 billion ton iceberg. A representation of the iceberg is shown in the lower figure generated on the computer by differencing the data shown in the upper figures. (Figure courtesy of S. Laxon, Mullard Space Sciences Laboratory, University College, London.)

Mean changes in surface elevation near the west margin of the Greenland ice sheet between the late summer of 1978 (Seasat) and 1987-88 (Geosat ERM). Each error bar represents one standard deviation of the mean for the change computed with respect to the Seasat surface, which is the datum. (Figure courtesy of C. Lingle, University of Alaska.)

Three dimensional perspective of Greenland (south of 72°N). Bands of color change every 500 meters of elevation. The elevations are derived from Seasat radar altimeter data. (Figure courtesy of H.J. Zwally, NASA/GSFC.)

et al., 1989). Recent work has also demonstrated the value of altimetry in monitoring the calving of tabular icebergs and their subsequent motion and evolution (Laxon, 1989).

Preliminary measurements using Geosat Geodetic Mission and Seasat altimetry have shown thickening of the southern half (approximately) of the Greenland ice sheet between 1978 and 1985-1986 (Zwally et al., 1989). This result has been debated (Douglas et al., 1990; Zwally et al., 1990). However, studies based on field data suggest that the Greenland ice sheet may indeed be thickening at higher elevations (Seckel, 1977; Reeh, 1985; Reeh and Gundestrup, 1985; Kostecka and Whillans, 1988). The northern half of that ice sheet, which is within more of a polar climatic regime, has not been measured with altimetry because of the 72° inclination of Geosat and Seasat.

The ERS-1 altimetry will cover most of the Greenland and the immense East Antarctic ice sheets, as well as more than half of West Antarctica, with orbits extending to 82°S. ERS-1 will permit direct measurements of regional mean changes in surface height.

The accuracy and coverage limitations of radar altimeters will permit useful measurements only in the higher accumulation regions and the smoother and flatter portions of the ice sheets. The deficiencies of radar altimeter measurements over the ice sheets are detailed Appendix A. A report of the National Academy of Sciences Polar Research Board (Meier et al., 1983) noted that " ... in measuring surface elevations a radar altimeter has sufficient accuracy for basic mapping, but a laser altimeter is needed to study changes."
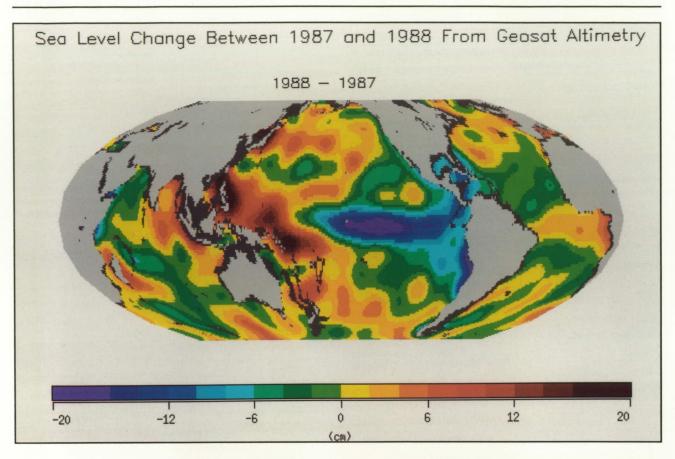
Continuing radar altimeter measurements are needed to map most of the ice sheets and provide estimates of elevation change in some parts of the ice sheets. In addition, a laser altimeter should be flown in polar orbit, not necessarily on the same spacecraft as a radar altimeter, for determination of overall ice sheet mass balance and the contribution of the ice sheets to sea-level change.

2.3. Global Sea-Level Change

An important scientific contribution of long-term altimetric missions could be the measurement of the change in the absolute level of the global sea surface caused by variations in the Earth climate system components. During the last Ice Age, some 18,000 years ago, the global sea-level was more than 100 m lower than at the present time. Recent results based on analysis of historic tide gauge data have indicated that the global sea-level over the last century has been rising at a rate of 1 to 3 mm/yr (National Research Council, 1990). In the coming century, simple climate models suggest that if greenhouse gas emissions continue at the present rate, sea-level rise will increase to nearly 5 mm/year over the next 40 years (Warrick and Oerlemans, 1990).

Changes in mean sea-level may occur with periods which vary from months to years, primarily because of changes in the heat stored in the oceans, or because of melting ice sheets. Substantial regional variations in sea-level, including large regions of both rise and fall are both expected and seen. Tide gauges, which are located primarily along continental coastlines and on a comparatively small number of mid-ocean islands, can never have a spatial distribution adequate for determination of large-scale to global changes. Only altimetry achieves the necessary spatial coverage.

The changes in sea-level attributed to thermal expansion and contraction related to the Earth's seasons have a signature that is 180° out of phase in the two hemispheres. An additional annual signal in the global sea-level is caused by the eccentricity of the Earth's orbit about the Sun; with possible longer period variations due to the long-

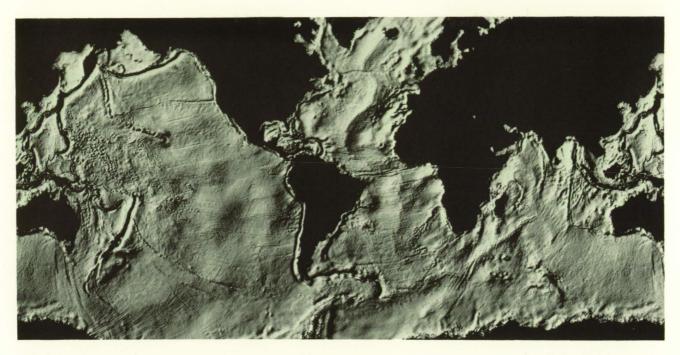Sea Level Change Between 1987 and 1988 From Geosat Altimetry

1988 — 1987

The change in annual averaged sea surface topography at scales greater than 1000 km between 1987 and 1988 based upon Geosat altimeter data. Large-scale regional changes, such as the impact of the 1986-87 ENSO event on sea-level, dominate year-to-year changes. (Figure courtesy of C. J. Koblinsky, NASA/GSFC.)

period perturbations in the Earth's orbit. The amplitude of the periodic global mean sea-level response to these stimuli has not been firmly established. Preliminary analysis of Geosat measurements indicates that the amplitude of the hemispherically averaged seasonal variation may be as high as 1.5 cm. Measurements from Geosat also suggest that interannual changes in sea-level have substantial regional variations, especially in the tropics. As the ocean circulation changes with climate, very complicated regional varying secular trends can be expected, as the resulting changes in flow patterns produce corresponding changes in the sea surface elevation.

Over longer periods of time (decades or longer), the change of heat stored in the deeper oceans, the melting of ice sheets, and the deformation of the lithosphere will contribute to sea-level change (National Research Council, 1990). Furthermore, the long-term motion of the Earth's surface due to post-glacial rebound, tectonic plate motion and polar ice cap melt has important long-term effects on the Earth's lithosphere and must be understood in order to interpret the tide gauge and altimeter measurements.

Born et al. (1986) suggested that changes in global mean sea-level over the period of a year can be monitored with an accuracy of a few millimeters by processing globally distributed altimeter data from well-tracked satellites. The approach is straightforward in concept and can be implemented for historic, current and future altimetric missions as part of the effort required to calculate the precise satellite ephemerides. If an independent calibration of the altimeter bias and its drift is available, then this approach can be used to monitor changes in the global sea-level. If the

The global mean sea surface for length scales less than 2000 km based upon Seasat and Geos-3 altimeter data. (Figure courtesy of J.G. Marsh, NASA/GSFC.)

altimetric sea surface height measurements from different satellite missions spanning a decade are computed in a consistent and accurate conventional terrestrial reference system, monitoring of the variation of the absolute global mean sea-level with an accuracy of 1 cm/decade is feasible.
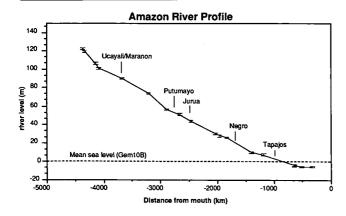
Nerem et al. (1992) have performed analyses using Geosat data which indicate that yearly averages of mean sea-level can be determined with a precision of a few millimeters, assuming the drift in the altimeter bias is known and orbit determination errors meet TOPEX/Poseidon specifications. Estimates from Geosat and Seasat have been limited by orbit determination uncertainties and by the fact that the altimeters are single-frequency instruments which are subject to ionospheric propagation errors. Further, the Geosat measurements are limited by a lack of water vapor range-delay measurements. These deficiencies should be corrected for TOPEX/Poseidon.

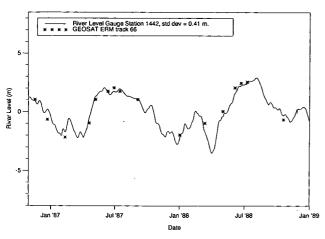**The potential of satellite altimetric data to measure the absolute sea surface to-** pography with a precision of a few centimeters and the launch of TOPEX/Poseidon provide an opportunity to start using the altimeter measurements for the monitoring of global mean sea-level changes.

2.4. Other Objectives

Satellite altimetry has proven itself very useful in a number of related areas. The outstanding example is undoubtedly its use in studying the marine gravity field (Douglas et al., 1987). Estimates of the mean sea surface and deflections of the gravity intensity vector (vertical) based on altimetric measurements have been especially useful (Sandwell and McAdoo, 1988). This surface can also be used for the detection of bathymetric features (Dixon and Parke, 1983). Mean sea surface undulations mainly represent geoid anomalies which reflect lateral variations in the lithosphere and mantle mass distribution. Altimetry data have provided medium- and short-wavelength geoid observations over the whole oceanic domain.

Amazon River Profile

Comparison Between GEOSAT Altimeter and River Gauge

A profile of the elevation of the Amazon River relative to the geoid (GEM-10B) in the summer of 1978 derived from Seasat altimeter data (Guzkowska et al., 1990) is shown in the upper figure. (Figure courtesy of C. Rapley, Mullard Space Sciences Laboratory.) Variations in the level of the Rio Negro in the Amazon Basin are shown with asterisks as derived from Geosat altimeter data and with a solid line from the river gauge in the lower figure. (Figure courtesy of C.J. Koblinsky, NASA/GSFC.)

Interpretation of this data over tectonic features such as seamounts, hot-spot swells, fracture zones, or mid-ocean ridges has greatly improved our understanding of the thermal and mechanical structure of the lithosphere and of its interaction with the underlying mantle (Sandwell, 1991; Cazenave, 1992).
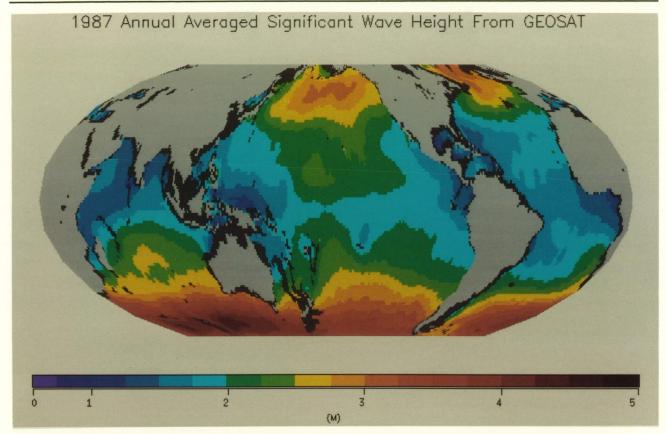
Of particular importance is the need for a fine spatial sampling of the marine geoid. Several major problems (e.g., segmentation and evolution of mid-ocean ridges) will take significant advantage of a better knowledge of the short-wavelength (< 50

km) geoid signatures. Continued high-quality altimetric measurements will improve both the horizontal resolution of the geoid and its accuracy, as shown by Marsh et al. (1992). In addition, this knowledge should help relax the repeat constraint for oceanographic missions. In this context, the 176-day exact repeat mission of ERS-1 is anticipated with great interest.

Altimetry also has the potential for increasing our capability for measuring inland water levels and wetlands (Rapley, et al., 1987; Guzkowska et al., 1990). Comparisons between Geosat measurements and Amazon River gauge observations show a difference of about 30 cm root-mean-square (rms) for temporal variations over 2 years. In remote regions of the world where environmental conditions are severe (such as the drainage basins of many major river systems) ground-based measurements are virtually impossible to collect for long periods of time. These observations would be extremely useful for hydrological models, as well as for the more practical matters of flood forecasts, design and operation of hydropower reservoirs, and navigation. Improvements in the altimeter tracker to permit faster tracker recovery after flying over rough continental surfaces, may permit these observations to be used for routine monitoring of inland water levels.

The altimeter measurement provides observations of wind speed and wave height. These measurements have proved to be useful for ocean wave and weather forecasting (Guillaume and Mognard, 1992). Continued altimetric measurements could play an important role in these forecasts for the practical aspects of military and civilian shipping.

The mapping of land topography is also a worthy goal for some form of satellite altimetry. However, the instruments and techniques required are quite different from the mapping of the oceans. Land topographic mapping techniques could be useful over the

The annual averaged Significant Wave Heights (average highest tercile of surface waves) for 1987 from Geosat altimeter data.
(Figure courtesy of C.J. Koblinsky, NASA/GSFC.)

ice sheets. The scientific goals and requirements for land topographic mapping, as well as the potential technology for carrying out this measurement have been discussed by the Topographic Science Working Group (1988), as well as Rapley et al. (1990). Satellite missions for land topography mapping are currently being pursued separately from the ocean and ice missions.

2.5. Summary

The scientific objectives of satellite altimetry have evolved over the past two decades because of the expanding measurement capabilities and the needs of the scientific community. In the coming decades, satellite altimetry can make a significant contribution to global change research. This measurement provides the only means to observe the global ocean circulation and its changes and the variation in the thickness of the polar ice sheets.

Altimetric measurements of these phenomena have been initiated with the Geosat Exact Repeat Mission (ERM) and the launch of ERS-1 in July 1991. They will be substantially enhanced in 1992 with the TOPEX/Poseidon mission. In order to explore the variations of these phenomena that are related to climate change, the measurements must be continued for several decades.

In the following two sections we outline the requirements and mission constraints that are needed to meet these objectives. The technology to meet these requirements is available. Section 5 describes the present technical capabilities and how these can evolve during the coming decade toward compact, lightweight, and flexible missions.

3. SCIENTIFIC REQUIREMENTS

3.1 General

In order to make global observations of the topography of the oceans and ice sheets with adequate accuracy for climate research there are three essential requirements. The first is continuity of coverage over several decades in order to detect climate-induced changes. The second is an evolution in system accuracy in order to separate the small climate-induced trends from errors in the measurements. Finally, the multiple missions that would be required will need to be cross-calibrated and an accurate measurement of the bias in each system, and its change, must be maintained.

Continuity

Multi-decadal continuity of coverage is crucial. Natural fluctuations occur in the ocean and ice sheet elevations on all space and time scales. The determination of statistically significant trends is nearly impossible if coverage is broken, if the data type and quality do not remain nearly homogeneous, or if the instrument bias is in error.

Significant changes in the ocean with the potential of influencing the climate have been observed to occur over decades. For example, decimeter changes in the surface topography of the western North Atlantic between the late 1950s and the early 1970s caused by thermal cooling have been detected from hydrographic measurements (Levitus, 1990). Interannual variations in the heat flux from eddies or strong boundary currents will require continuous altimetric measurements because the dominant time scales of these features are only a few months.

Over the polar ice sheets, it will be critical to maintain the high-latitude coverage because the time required to distinguish long-term mean changes in surface height from the interannual to multiyear background variability is substantially longer than the probable lifetime of a single satellite mission. For example, snow-pit studies along Antarctic traverse routes have shown that the interannual variability for snow accumulation rates can range from ± 25% to over ± 50%, and ± 25% variations can be expected for consecutive 10- to 20-year periods (Young et al., 1982).

System Accuracy and Precision

Climate change will most likely manifest itself as weak, secular drifts superimposed upon the signals inherent in the natural background variability. The spatial scale over which such trends will occur is not known, but climate models suggest that they will range from the regional to global. Consequently, observing systems must be designed to detect weak trends in noisy backgrounds over long time periods.

Comparisons between Geosat and Seasat altimeter measurements in order to examine decadal changes in the topography of the oceans (Haines, 1991a) and the Greenland Ice Sheet (Lingle et al., 1991; Zwally, et al., 1989) have been carried out. These studies point out the need for improvements in system accuracy and precision

in order to carry out multiple satellite missions for the detection of climate-induced changes.

The time varying components of the ocean circulation produce sea surface signals ranging from about 1 cm to 1 m. Initial estimates of interannual large-scale (> 1000 km) variations in surface topography from Geosat altimetry suggest that < 10 cm variations are the most common. Numerical models have suggested that surface heating at mid-latitudes and wind forcing in the tropics are the principal causes of the larger fluctuations (10 cm) in sea surface topography at annual and interannual time scales. Fluctuations in surface topography resulting from changes in the deep ocean circulation, which will be important for understanding long-term climate, are estimated to be a few centimeters at most. The time-invariant component of the circulation produces similar surface elevation signals; the present uncertainty in the time-invariant component is about 10 cm over horizontal scales greater than 2000 km.

Over ice sheets, the 10-cm single-pulse precision of the laser altimeter will enable 1-cm measurements of average elevation change over ice sheet areas on the order of several hundred kilometers by averaging a sufficient number of crossover differences. Compared with laser altimeters, radar altimeters will always be limited in precision over the ice sheets because the size of their footprint (> 1 km) is much larger than that of the laser altimeter (< 100 m).

The system accuracy and precision of satellite altimeters should be maintained or improved. The TOPEX/Poseidon capability is presently at 13-cm rms accuracy, computed over a 10-day repeat cycle. Precision orbit uncertainty remains the dominant error term in the budget. In the coming decade, the radial orbit error should approach 5 cm through anticipated improvements in gravity modeling and tracking technology.

Cross-calibration

Data from altimeters on different platforms need to be cross-calibrated to ensure a coherent long-term monitoring of the ocean or ice sheet changes. Direct cross-calibration of altimeters flying contemporaneously can be performed by analyzing the crossover differences. More generally, a rigorous comparison of the altimetric data from different missions requires: calibration of the altimeter measurement from mission to mission; consistent precise orbital positioning systems; precise station coordinates for tracking systems determined with the International Earth Reference System (IERS); instruments to provide a precise determination of the tropospheric and ionospheric range corrections; surface measurements to validate estimates of the skewness and em bias produced by surface gravity waves; and archival of all data for future reprocessing.

3.2. Ocean Circulation

Studies leading to the TOPEX/Poseidon design and analysis of the available altimetric data imply certain quantitative characteristics for any altimetric mission which is to be useful for observing the ocean circulation.

Coverage

Global coverage is required. This simple statement reflects the fact that to understand the behavior of a fluid system, one must be able to observe all of it. In the case of the ocean, polar, mid-latitude and tropical regions must be observed.

Scales

All dominant space/time scales must be measured. The ocean is a global fluid governed by complex motion on a wide range of spatial scales predominantly between the

Rossby radius of deformation (about 25 km) and basin scales (10,000 km) and on time scales between days and geological periods. Neither spatial nor temporal scales exhibit spectral gaps, and there are mutual energy transfers between different scales. No frequency or wavenumber bands can be ignored either kinematically or dynamically during studies of global changes of the general circulation of the oceans. Measurements of the large-scale topography require the most system accuracy (e.g., TOPEX/Poseidon or better), especially in the orbit and range corrections, whereas observations of the larger mesoscale variations can be made with a less accurate system (e.g., GFO).

Marine Geoid

The mean sea surface measured by the altimeter is a sum of the geoid and the surface topography. Present-day models demonstrate that improved spatial resolution of the gravity field is required to resolve the mean circulation at shorter length scales. The principal errors in this calculation are in the estimate of the geoid and in the systematic radial orbit errors. These can only be reduced with significant improvements in the model of the Earth's gravitational field.

Quantitative knowledge of the shape of the Earth's gravitational field, especially the marine geoid, must be greatly improved at scales less than 2000 km. Dedicated gravity missions, such as ARISTOTELES, are the only method for providing the necessary improvements.

Ocean Tide Models

The development of accurate tide models is required. A recent performance evaluation of the algorithms presently used to predict tidal corrections in satellite altimeter Geophysical Data Records (GDRs) has been given by Le Provost et al. (1991). They reached two key conclusions. First, the

Schwiderski (1980, 1983) solutions used for these predictions are not accurate enough to ensure a few-centimeter accuracy everywhere. Second, the number of constituents to be included in open ocean tidal predictions must be increased.

The ongoing efforts within the ERS-1 and TOPEX/Poseidon research groups need to be continued, in order to improve our knowledge of the ocean tides to an accuracy of a few centimeters rms. Three key issues must be addressed with TOPEX/Poseidon measurements: modeling tides over the continental shelf; determining the long-period tides; and improving the solar tides. If this latter effort is successful, it may be possible to remove modeled solar tides from Sun-synchronous data to an acceptable accuracy.
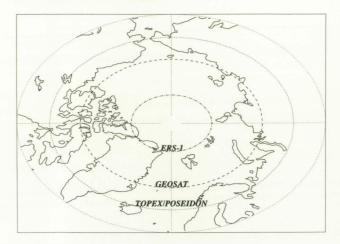
3.3. Polar Ice Sheets

Altimetric measurements of ice sheet topography are quite different from estimates of sea surface topography. The geographic coverage and characteristics of the surface are quite different. This leads to four ice sheet-specific requirements:

Laser Altimeter
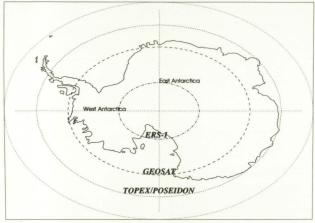
A laser altimeter is needed for determination of ice sheet mass balance. The required precision of 10 cm, degrading to no more than 50 cm over slopes of several degrees, exceeds the capabilities of practical radar altimeters.

Inclination

The satellite orbit must have an inclination of at least 82° of latitude. This will ensure significant coverage of the major polar ice sheets. At these inclinations, most of the Greenland, West Antarctic and East Antarctic ice sheets can be monitored. Consideration should also be given to the flight of an instrument in a 90° inclination

The highest latitude extent of the TOPEX/Poseidon, Geosat and ERS-1 altimeter missions.

orbit to provide coverage of all of Antarctica. Such a mission should be repeated on a 10- to 20-year cycle for long-term studies of mass balance variations.

Non-exact Repeat Orbit

A non-exact repeat orbit is desirable. Over ice sheets the cross-track gradient is typically several meters per kilometer and may change sign over along-track distances of about 10 km. Therefore, crossover analysis is the principal method for analysis of ice sheet elevation change and repeat-track analysis is of limited value for ice sheet studies. A non-exact repeat orbit greatly increases the number of crossover locations for analysis of elevation changes and provides more complete coverage of the ice sheets.

Radar Waveform Data

Altimeter radar waveform data must be available for ground processing. The altimeter signal over the ice sheet is a much more complicated return than from the ocean (Zwally et al., 1989). Present onboard waveform trackers are unable to accurately select the correct range. Ground-based post-processing of the waveforms is required. High-frequency (at least 20 Hz) averaged waveforms must be transmitted to the ground.

3.4. Global Sea-Level Change

There is less experience in estimating the global rise in sea-level and the absolute level of the sea from altimetric data than for either the ocean circulation or polar ice sheet problems. However, attempts to make this measurement from tide gauges have given estimates of the range of the signal and the significant issues that must be addressed by satellite measurements. This signal is different than the observation of local ocean or ice topography because of global averaging, the importance of systematic errors, and the small size of the signal. Two specific requirements are worth noting:

Reference System
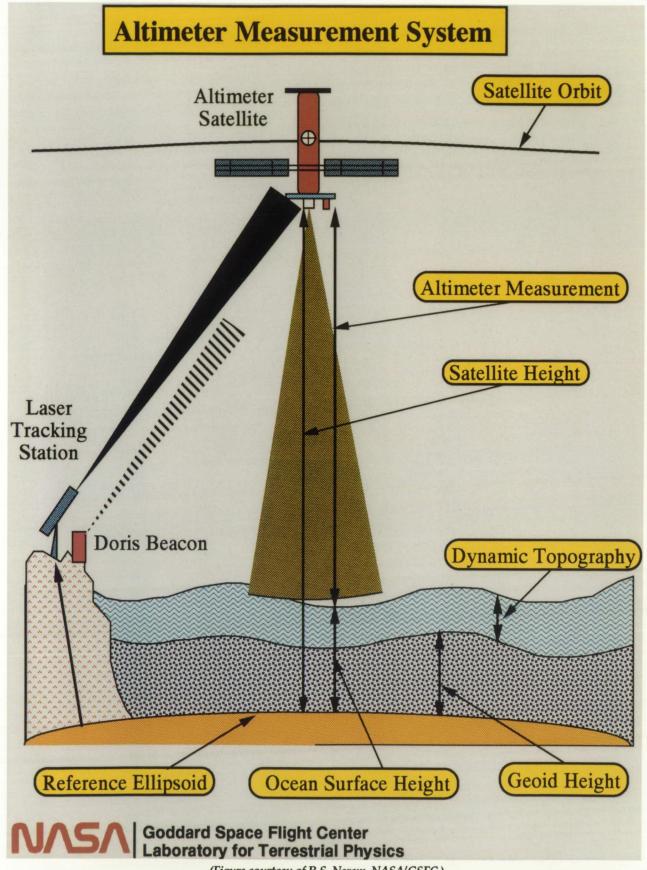
An accurate conventional terrestrial reference system must be established and maintained. This requires accurate modeling of the gravitational constant and tracking station coordinates, the tectonic motions at the tracking sites, the Earth orientation vector, the precession and nutation, and the tidal loading and Love numbers for the Earth.

In order to tie the results from different missions together, thus providing measurements of mean sea-level spanning decades, it is necessary to reference all re-

sults to the highly accurate, well-controlled IERS. The Satellite Laser Ranging (SLR) system is part of it and is the only method for unambiguously measuring the center of mass of the Earth to 1 to 2 cm (Ray et al., 1991). Consequently, it is important that the operation of IERS, and SLR be continued and that ties between IERS and all other tracking systems (GPS, DORIS, PRARE) be established and maintained.

Systematic Errors

Knowledge of global systematic errors and biases must be known for each element of the altimeter system to 1 mm. Systematic biases in the measurement system can be estimated using ground-based observations from a fixed point to the satellite, using lasers or transponders. It needs to be established whether these point measurements determine the global averaged errors.

Altimeter Measurement System

Altimeter
Satellite

Satellite Orbit

Altimeter Measurement

Satellite Height

Laser
Tracking
Station

Doris Beacon

Dynamic Topography

Reference Ellipsoid

Ocean Surface Height

Geoid Height

NASA | **Goddard Space Flight Center**
Laboratory for Terrestrial Physics

(Figure courtesy of R.S. Nerem, NASA/GSFC.)

4. MISSION CONSTRAINTS

The objectives and requirements shape the mission. The system accuracy influences the payload. The space/time coverage and accuracy restrict the orbit configuration.

4.1. System Accuracy

The required and useful overall accuracy of an altimeter mission can be reached only if each of the sub-elements are pushed to the limits of what can be achieved at the present time, and if a full calibration effort is conducted. The following subsections discuss, in turn, the sub-elements and their major sources of error, as well as the extent to which each error must be reduced.

Precision Orbit Determination

The orbits of the Seasat and Geosat satellites have been determined with errors of about 50-cm rms (Shum et al., 1990; Haines et al., 1991) using imprecise tracking measurements and a preliminary gravity model developed for TOPEX/Poseidon. The orbit errors are mainly on the scale of the Earth circumference and this confinement to long wavelengths is the basis for many different orbit error removal schemes. These filters have little impact on the estimated oceanic mesoscale and regional signals, but remove a significant part of the large-scale signal.

Quantitative observations of the large-scale ocean circulation and ice-sheet elevation require decimeter (or better) orbit determination.

Altimeter Range Measurement

Instrument noise should be small and random. If slowly varying measurement errors are present, they should be removable by calibration techniques. The measurement error should be insensitive to dynamical effects such as acceleration. Off-nadir pointing angles induce changes in the waveform shape which in turn affect the range estimation. The amplitude of this error depends on many factors such as the satellite altitude, the size of the antenna, the tracking and the estimation software used. It is typically recommended that the platform be stabilized to keep the off-nadir pointing angle below 0.6°, and that this angle be measured with an error less than 0.1°.

The radar should have a fast acquisition time after leaving continents, locking on the sea surface as rapidly as possible. A calibration of the radar range bias must be available in the spacecraft through an internal timing loop, where performance is validated through periodic calibration overflights of ground-based SLR sites. The stability of the onboard clock must be monitored from the ground. Post-processing of the altimeter waveforms over the ocean to accurately remove skewness bias must be evaluated.

The radar altimeter should have the agility to follow ice slopes less than 10 m/km, at backscatter coefficients as low as -20 dB. Adaptive altimeter trackers can be built with different functional characteristics for ice and ocean. A further essential require-

ment is for a tracker capable of operation over all surface types without loss of lock. Andrewartha et al. (1988a; 1988b) describe initial design work on an adaptive bandwidth tracker for ESA's POEM-1 altimeter RA-2. Performance simulations have demonstrated an ability to maintain track over all types of terrestrial surface and to rapidly optimize bandwidth (height precision) following surface transitions.

Above the ocean, the altimeter range measurement error should be a white noise. The deviation should not exceed 2-cm rms for 1-Hz sampling. Above continental ice sheets, the altimeter should also have an agile tracker that can recover from signal loss and detect larger variations in terrain than are observed over the ocean.

Altimeter Range Corrections

The space/time characteristics of the atmospheric/ionospheric refraction and surface bias corrections are rather different from those of the oceanic mesoscale circulation and are more similar to the large-scale ocean circulation. Nevertheless, rapid, small-scale variations of the troposphere and ionosphere induce variations in the altimeter measurement that can be mistaken for ocean signals. Strong atmospheric fronts can create such problems. Also, the large-scale seasonal and interannual variations of the tropospheric corrections are poorly known. In some cases, they are correlated with the ocean atmospheric forcing and the ocean dynamical response. Therefore, one must carefully monitor the ability of all altimetric systems to maintain coherent range corrections on the long term. Surface scattering induces a bias in the altimeter range measurements (EM and skewness biases). These biases are linked to the wave characteristics and the properties of the onboard sea-level tracker.

All altimetric systems should consistently provide means of estimating the

range refraction and surface effect errors with centimeter accuracy at the spatial scales of the significant altimeter signal (greater than 25 km). In all of these range corrections, systematic biases and errors must be measured and reduced.

4.2. Orbit Configuration

The objectives and requirements of satellite altimeter missions also constrain the orbital configuration. The inclination determines the geographic coverage; the eccentricity has an impact on the range measurement and attitude; the altitude has an impact on the errors in the orbit determination; and the repeat cycle impacts the temporal sampling and removal of the geoid. These issues are described below.

Inclination

Simple geographical considerations set bounds on the inclination. For example, the minimum value of the inclination needed to observe the Antarctic Circumpolar Current is 66°. A value close to 90° is required to observe the Antarctic polar ice cap. However, such high inclination is not favored for missions focusing on the ocean. Indeed, high inclination reduces the angle between the ascending and descending tracks. If this angle is too small, the zonal and meridional components of the sea surface slope cannot be separated accurately. Inclination also plays a role on how ocean signals are aliased in the altimetric data (Parke et al., 1987).

Emphasis should be placed on maintaining a high-accuracy altimeter system at an inclination extending to at least 66° latitude for ocean observations and 82° to cover most of the polar ice sheets.

Eccentricity

The dynamic range of altimetric measurements is less for smaller eccentricities, which makes the selection of pulse-repetition frequency of the radar easier to select. In addition, the spectrum of the orbit perturbations has peaks with amplitudes that are proportional to e^q where e is the eccentricity and q is an integer. If e is weak (on the order of 10^{-3}), this spectrum only has a few main peaks, the secondary peaks (q equal or larger than 2) being negligible. In that case, the main peaks are clearly identified and their amplitudes can be very precisely determined. This allows for the corresponding orbit error to be corrected.

Satellite altimeters should fly in orbits with a very small eccentricity.

Semi-Major Axis (Altitude)

For a given precision, the power demand of radar altimeters decreases when the altitude decreases. In addition, low altitude reduces potential damage and risk to the spacecraft instrumentation from radiation. On the other hand, orbit precision increases with altitude as the effects of atmospheric drag and errors in models of the gravity field decrease. The TOPEX/Poseidon orbit was established rather high (1335 km) to minimize these effects.

In the future, as our knowledge of the gravity field improves, and models are developed to account for the non-gravitational forces, it may be possible to compute precise (decimeter) orbits for lower altitude spacecraft. The knowledge of non-gravitational forces can be improved through the use of two methods. First, the use of improved (denser) tracking networks will allow a more continuous monitoring of these forces on the orbit determination. Secondly, microaccelerometer instruments on the spacecraft can provide accurate measurements of these forces (See Appendix E).

Satellite altimeter missions should be flown at altitudes of at least 1200 km to minimize orbit determination errors. However, given our constantly improving knowledge of the gravity field and non-gravitational forces, a precise orbit determination (10-cm rms or better) should be possible for orbits at altitudes well below that of TOPEX/ Poseidon in the near future.

Repeat Cycle

Both repeating and non-repeating orbits can be envisaged for altimetric missions. Exact repeat missions provide a geoid determination along the ground tracks by averaging the elevation measurement at each point. It is generally required that the orbits of altimetric satellites repeat to within ±1 km at the equator; this helps considerably in separating the ocean variability signal from variations in the geoid sampled along shifting ground tracks.

The geoid slope exceeds 1.5 cm/km over more than 35% of the global ocean. This slope will be difficult to estimate on short distance scales with better than 25% precision. This error will have the most impact on estimates of the mesoscale. The along-track wavenumber spectral characteristics of the contamination by the cross-track geoid are very similar to those for the ocean variability over more than half of its surface.
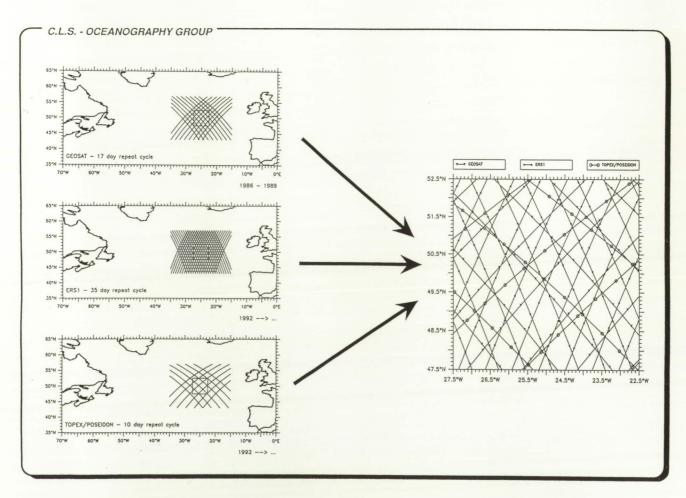
The repeat-track orbit constraint of ±1-km repeatability cannot be relaxed for global change research. In order to build long time series of altimeter observations there are advantages in repeating the ground tracks of previous high-accuracy missions.

Sampling Strategies

The space and time scales of the ocean eddy field lead to a conflicting sampling requirement for altimetric systems. The short time scales of equatorial and boundary current dynamics require short sampling rates (a few days) while the spatial scales of energetic eddies (approaching 50 km in mid-latitudes) demand at the same time, dense spatial sampling. A single satellite cannot satisfy those requirements and therefore, multiple simultaneous radar altimeter missions are strongly urged for ocean study and monitoring purposes. The optimal sampling pattern for several contemporaneous missions is unresolved. The answer is not unique and will depend on the goals of these missions.

The choice of the repeat period for a single altimeter mission is a compromise between spatial and temporal resolution because the finer the time resolution, the coarser the spatial sampling. Over the past two decades, the best compromises for single altimeter sampling were found for 10- to 20-day repeat periods. Typically, an orbit with a 20-day repeat period has a ground track spacing of about 150 km at the equator and 100 km at 45° latitude. This spacing is doubled for a 10-day repeat period. Such sampling characteristics are insufficient to provide a good resolution of western boundary currents where instabilities with a typical size of 200 km can develop in about 10 days.

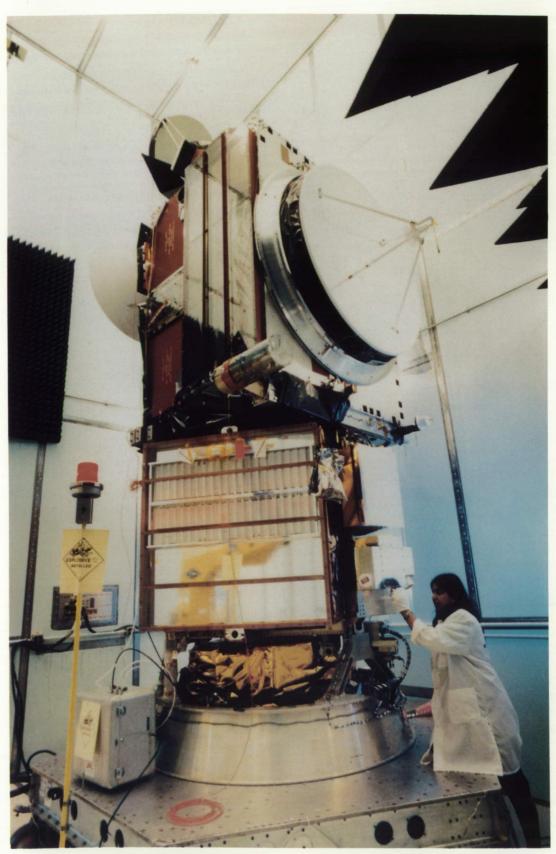For larger scales and slower evolutions, a single satellite may suffice. However,

The spatial sampling of a small patch in the North Atlantic with Geosat, TOPEX/Poseidon and ERS-1 altimetry. The combined sampling is shown on the right. (Figure courtesy of F. Blanc, CLS Argos.)

because of the complex observation pattern, aliasing of high-frequency, high-wavenumber features is very noise sensitive. As the large-scale signals are much less intense than the mesoscale signals, this may be a serious, yet unassessed, difficulty. Multiple altimeter missions will significantly improve mesoscale sampling and reduce such aliasing.

It is recommended, both for mesoscale and large-scale studies, that multiple altimetric satellites be flown contemporaneously.

The most likely scenario for multiple missions will be the result of various agency plans and requirements. There is a need for interagency coordination in mission planning. We recommend the formation of an international science steering group to facilitate the development of a coordinated altimeter program between agencies.

We recommend an extensive research effort with altimeter data assimilation using appropriate ocean models and simulated sampling patterns corresponding to different orbital scenarios to determine the most efficient sampling with multiple satellites.

The TOPEX/Poseidon spacecraft near completion. (Figure courtesy of Fairchild Space Industries.)

5. TECHNICAL CAPABILITIES

The basic altimeter mission requires a number of instruments and measurements, including: the radar altimeter; boresighted wet troposphere and ionosphere range correction measurements; the ground- and satellite-based components of the tracking system; and the verification measurements from the ground. In addition, ground-based processing and a data system are very important for enhancing the radar measurement, providing the precision orbit determination, and distributing the measurements to the science community. Considerable progress has been made in the development of all systems over the past decade based on experience from Geos-3, Seasat and Geosat and in the planning and construction of ERS-1 and TOPEX/Poseidon. In this section, we summarize the current capabilities and the direction of future development for these components.

5.1. Radar Altimeter

The major advance in radar altimeter design in the past decade has been the solid-state transmitter. In solid-state transmitters, a transistor instead of a Traveling Wave Tube (TWT) is used for power amplification. Solid-state design goals are reduced mass and power demand with increased reliability and long-term stability. Achieving these goals will make altimeters suitable for a wider variety of flight opportunities, as well as improve system performance.

Solid-state designs have been developed in France by CNES and in the U.S. by The Johns Hopkins University Applied Physics Laboratory (APL). The first flight models of these new altimeters will be on the TOPEX/Poseidon mission. The Poseidon altimeter will be a solid-state Ku-band radar designed by CNES, and the TOPEX C-band solid-state radar will be based on an APL design. Preflight simulations have shown that these instruments will achieve their basic goals. In-flight assessment will take place in 1992 and will provide very valuable data for the design of future missions. A description of Poseidon is presented in Appendix B.

In addition to solid-state transmitters, additional improvement can be made in the Radio Frequency (RF) design portion of an altimeter. As shown by Poseidon, a substantial reduction in size is possible by using modern technology in the digital subsystem. In addition, changing construction materials to composites or titanium would reduce weight and volume.

In parallel with establishing a compact altimeter there also needs to be an examination conducted of the supporting spacecraft subsystems; e.g., tape recorders, power, telemetry, command, etc. The power system (and its associated battery, solar cell, array drive, etc.) is another heavy component that could be redesigned. Significant developments are expected in these areas over the next decade and they will have to be integrated into a comprehensive hardware approach.

We recommend a focused effort by altimeter development groups to produce lightweight and compact altimetric systems for future missions.

Near real-time processing of the altimeter waveforms should be a routine procedure carried out by the satellite project data system, either with on-ground or onboard processing. Corrections need to be made for the effects of altimeter mispointing, sea surface skewness, range acceleration, etc. An intelligent and efficient waveform tracking algorithm will enhance the scientific return near coastlines and islands, over ice sheets, and over ground-water areas such as lakes and rivers.

Advances in waveform tracking methodologies are required for future altimeters to effectively track waveforms accurately over features such as calm and rough sea surfaces, smooth ice, ice terrain, land terrain, vegetation and other surface features.

The full capability of altimeter measurements should be examined in the next decade. For example, radar altimeters will be used to measure rain in the Tropical Rainfall Measuring Mission. It should be determined whether it is practical to include this measurement in the ocean and ice mapping radar altimeters.

5.2. Radar Range Corrections

The altimeter range measurement is subject to errors from a number of sources. In the atmosphere, the altimeter signal is delayed by the presence of free electrons in the ionosphere, as well as water vapor and dry gases (primarily oxygen) in the troposphere. Some of these corrections require simultaneous measurements from the spacecraft that are boresighted with the radar signal.

Ionosphere

The ionosphere range correction requires a measure of the ionosphere Total Electron Content (TEC) integrated along the altimeter sub-satellite line of sight. For Geos-3, Seasat, Geosat, and ERS-1, this correction was computed from a model using non-simultaneous ground-based observations (e.g., Klobuchar, 1987). These models have an accuracy of about 50% of the ionospheric range delay, which can range from 2 to 20 cm (Musman et al., 1990).

The variations in the ionospheric delay have large spatial scales and are associated with the diurnal, annual and interannual variations in solar activity. Consequently, a direct measurement of this correction is needed for altimeter missions that pursue global climate research objectives. Several methods for making this measurement from a spacecraft have been proposed: dual-frequency altimetry; dual-frequency DORIS, GPS or PRARE tracking measurements, and nadir-viewing ionosonde measurements. These techniques are described in Appendix C. These systems will be evaluated and intercompared over the next 5 years.

We recommend an extensive analysis of the TOPEX/Poseidon ionospheric range correction and comparison with assimilative models in the next few years and a dedicated effort in the coming decade to determine the most efficient and economical means for making this measurement. However, until an alternative technique has been demonstrated to accurately make the correction, the mission design should be based on a dual-frequency altimeter.

Wet Troposphere

The variability of the water vapor content in the atmosphere is rich in both spatial and temporal scales. Energetic events associated with weather fronts have temporal

scales of hours to days and spatial scales of tens to hundreds of km. Diurnal fluctuations have been found to cause radar range delays in excess of 3-cm rms. These variabilities cannot be properly dealt with by either non-coincident satellite measurements or models. The use of an onboard nadir-looking microwave radiometer is the only viable approach. Several independent studies have shown that it is feasible to merge the radar altimeter and passive microwave radiometer antennae into a single system. It should be determined if this is a viable approach for ultimately reducing overall mission costs.

Altimeter systems must include boresighted passive microwave measurements of total columnar water content in order to accurately model the tropospheric range delay of the radar range signal.
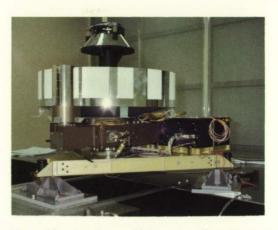
Dry Troposphere

The range delay caused by the tropospheric dry gases is proportional to the sea-level pressure. For correction with 1-cm accuracy, sea-level pressure has to be known with an accuracy of 4 mb. This accuracy should be achieved globally, except perhaps in the Southern Ocean, by future atmospheric models that utilize satellite scatterometer observations of ocean surface winds (Brown and Levy, 1986).

A thorough analysis of the accuracy of the dry tropospheric range correction should be conducted with TOPEX/Poseidon measurements.

5.3. Laser Altimeter

Satellite laser altimeters have been built and flown in space. The Martian topography will be mapped in the next few years with the Mars Observer Laser Altimeter

The Mars Observer Laser Altimeter undergoing tests at Goddard Space Flight Center (Figure courtesy of B. Johnson, NASA/GSFC.)

(MOLA). GLRS-A is the altimeter portion of the Geodynamics Laser Ranging System (GLRS) designed for NASA's Mission To Planet Earth. GLRS-A is designed to measure range to the surface with an intrinsic single-pulse precision of better than 10 cm. It will be used to measure ice sheet heights, slopes, surface roughness, and changes in ice sheet thickness at the cm level. The primary purpose of GLRS-A is determination of ice sheet mass balance and the ice sheet contributions to sea-level change. The secondary purpose is measurement of cloud, planetary boundary layer, and aerosol height distributions with a vertical resolution of about 75 m from the surface to a height of 30 km.

In order to improve the determination of changes in ice sheet elevation, GLRS-A should be flown at the earliest opportunity.

5.4. Precision Orbit Determination

A goal of future altimeter missions should be to improve on the system accuracy expected from TOPEX/Poseidon. The radial orbit accuracy of these missions should be better than 10 cm. To achieve operational precision orbits to this accuracy level, improved orbit determination techniques will be needed.

Many factors determine how accurately the orbit of a satellite can be determined:
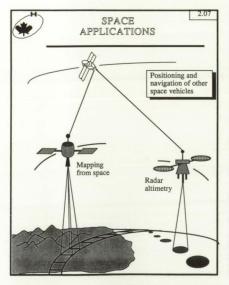
- The precision of the measurements of the satellite's range and range-rate;

- The accuracy of the models describing the gravitational and non-gravitational forces that influence the satellite's motion; and

- The coverage of the tracking network and the accuracy of the position of the tracking stations.

A review of the precision tracking systems that potentially will be available during the mid-1990s and beyond is presented in Appendix D. It is expected that any one of these systems would be sufficient, when combined with the appropriate modeling activity, to provide orbits with an accuracy of 10 cm. Experience and comparisons of the capabilities of these tracking systems should be available with ERS-2 and TOPEX/Poseidon over the next few years.

Extensive international efforts are underway to improve models of the Earth's gravity field. This work must continue in order to achieve accuracy at high inclination and/or low altitude. Modeling of the non-gravitational forces is also progressing. Direct measurement of the non-gravitational accelerations on the spacecraft is another promising solution. Such measurements can be obtained from a microaccelerometer, which is described in Appendix E.

New, denser tracking systems are becoming available. GPS will permit nearly continuous tracking. With this approach, the orbit determination is only weakly dependent on dynamical and gravity field modeling. Model errors thus tend to have a smaller impact on the precise orbit determination. With a dense ground-based tracking network, precise orbit determination is also possible using more usual dynamical orbit determination techniques, as shown by the first results of DORIS on the French Satellite Pour l'Observation de la Terre - 2 (SPOT-2). The dynamical approach also yields an *a priori* determination of the residual orbit error spectrum. A large fraction of this error can then be, *a posteriori*, filtered out. In order to detect, and then filter out, long periodic terms in the orbit error, orbital computations over very long spans of data should be encouraged.

Positioning and navigation of satellites from GPS. (Figure courtesy of Canadian GPS Associates.)

PRARE ground system.

SLR tracking site. (Figure courtesy of Crustal Dynamics Project Office, NASA/ GSFC.)

The dramatic improvement in tracking systems and capabilities in dynamical orbit prediction in the coming decade lead to a number of specific recommendations:

A continued development effort in dynamical orbit determination, including improvement in gravity and non-conservative force modeling, as well as the arc-length over which the orbits are computed. In the coming decade, gravity models must be improved using TOPEX/Poseidon and ERS-1 altimetry and tracking observations.

The capability of GPS tracking to provide kinematic orbit prediction must be assessed with TOPEX/Poseidon.

The future of GPS tracking must be assessed. Federal agencies should encourage the Department of Defense (DOD) to turn off anti-spoofing and selective availability during peacetime to permit the unclassified community full access to the GPS. In addition, NASA should develop the ability to work with Y-codes in a classified environment or develop a codeless receiver.

The in-flight capabilities of the tracking systems (i.e., SLR, GPS, DORIS, and PRARE) must be compared during the TOPEX/Poseidon and ERS missions.

The utility of altimeter data as a tracking measurement must be assessed with TOPEX/Poseidon measurements; does this technique corrupt the geophysical/oceanographic signal in the altimetric elevations?

5.5. Calibration

The objective of the calibration 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

DORIS ground station. (Figure courtesy of CNES.)

geophysical algorithms and associated reduced data. The final geophysical data set consists of verified measurements of height, significant wave height, wind speed (derived from the backscatter coefficient), and total electron and water vapor content.
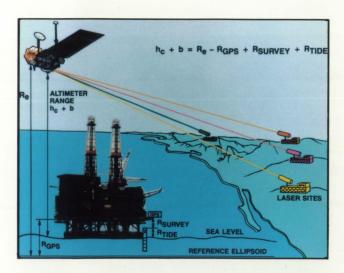
The calibration process should determine the accuracy of these geophysical measurements. In particular, it is essential that the height bias or change in the height bias be measured and monitored throughout each mission. This information is vital to maintaining continuity in long time series of global sea-level spanning several different altimeter missions.

The calibration process begins prior to launch and continues throughout the mission. The data processing system must be fully functional prior to launch to verify that the 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 of any future missions.

During the first few months after launch, engineering assessment and calibration would be high-priority activities. Based on past experience, engineering assessment requires about 1 month and the initial calibration of geophysical parameters will require about 6 months.

The altimeter height measurements should be verified through analysis of and comparison with ground-based laser ranging, GPS measurements, and *in situ* data in a manner similar to that proposed for TOPEX/Poseidon (TOPEX/Poseidon Project, NASA/CNES Joint Verification Plan, 1991) and ERS-1 (Francis and Vusmann, unpublished ESA report, 1988). Total electron content may be verified by comparisons with results obtained using GPS, or Faraday rotation data. The wet tropospheric range correction can be calibrated using radiosondes or upward looking water-vapor radiometers, such as employed at radio astronomy observatories. Wave height and wind speed should be verified by comparison with buoy data. The precision orbits should be verified by an analysis of tracking data residuals, analysis of altimeter crossover residuals, and ephemeris intercomparison.

Calibration activities should continue throughout the mission at a lower level after the initial calibration period. Only after the algorithms, data products, and processing procedures have been verified, should production of the Geophysical Data Records

A tide gauge site on the island of Majuro in the Republic of Kirubati. (Figure courtesy of G. Mitchum, University of Hawaii.)

(GDRs) begin. Thereafter, modifications and updates of the algorithms may be made, if necessary, subject to project-established review and approval procedures. Calibration after the initial period would consist primarily of continuing to monitor the quality of the geophysical measurements and the precision orbits. If this monitoring activity reveals unexplained accuracy deviations, then an intensive reverification effort similar to that performed during the initial calibration period will be necessary.

The capabilities of all calibration systems for global change research must be assessed with the TOPEX/Poseidon measurements.

5.6. Launch Vehicles

A goal of future altimeter missions is to reduce the weight and power of the instrumentation for flexibility and economy in the selection of a particular launch vehicle. There are essentially three cost classifications for launch vehicles: low ($9 to 25 M), medium ($50 to 150 M), and high (> $150 M). The TOPEX/Poseidon Ariane 42 Launch Vehicle

The NASA calibration and validation facility for TOPEX/Poseidon off Pt. Conception. (Figure courtesy of TOPEX Project Office.)

is in the upper range of the medium-cost vehicles. Its performance is suitable to achieve the requisite orbit, although a Delta or Atlas rocket could also be used. One choice for a future mission might involve a free-flying satellite altimeter on a lightweight and inexpensive launch vehicle as in the GFO design specification.

The recommendations for payload weight and power reductions described in this document should be considered in a Phase A-type study to determine if a low-cost launch, free-flying altimeter mission with TOPEX/Poseidon-type accuracy can be achieved.

A nighttime launch of Ariane. (Figure courtesy of CNES.)

6. SUMMARY AND RECOMMENDATIONS

Satellite altimetry is the only instrument that can make long-term global observations of the ocean circulation and polar ice sheet mass balance. These measurements are essential for improved understanding and predictability of climate change. This report has articulated a number of studies that need to be carried out over the next few years in order to provide improved altimetric measurements in the post-TOPEX era for global change research. The two fundamental recommendations of our report are:

A succession of high-accuracy satellite altimeter systems designed for ocean and ice observations are needed, beginning in 1997 at the latest, to establish an uninterrupted time series over the global ocean and major ice sheets for at least the subsequent 20 years.

The greatest scientific benefit will be achieved from future altimeter missions with a series of dedicated high-precision spacecraft, for which the choice of orbit parameters is unencumbered by sampling requirements of companion instruments.

In order to work toward these goals there are a number of issues which need to be addressed by the TOPEX/Poseidon Science Working Team over the next few years. In addition, there are several other issues which require an analysis independent of the TOPEX/Poseidon mission. Finally, a vari-ety of altimeter missions have been proposed for the end of the decade and beyond; these programs can now be considered in the context of the objectives and requirements presented in this report. These recommendations are summarized in this section.

6.1. TOPEX/Poseidon Science Working Team Studies

The TOPEX/Poseidon mission will test a new level of accuracy in altimetric measurements. In order to achieve improved accuracy, a variety of new systems will be implemented. These new systems must be assessed for accuracy in the very near future in order to have an impact on future missions. In addition, new physical models will be generated from the TOPEX data that can be used by future missions. Consequently, the TOPEX/Poseidon Science Working Team (T/P SWT) should task subgroups with the following issues that will benefit future altimeter missions:

Assessment of Tracking Systems

The three tracking measurement systems (SLR, GPS and DORIS) on TOPEX/Poseidon need to be carefully examined in terms of their impact on precision orbit determination. The systems should be examined on an individual basis and in combination. The best mix of observations and modeling approach for the most accurate orbit must be identified. An assessment of the observation density must be made. The GPS system must be examined both with and without the selective availability and

anti-spoofing degradations. Both the DORIS and GPS systems should be compared against the laser tracking systems for overall accuracy and determination of the Earth's center of mass. Finally, the value of using the altimeter range measurement as a source of tracking data must be evaluated. How much of the oceanographic signal is removed from the height estimate when the altimetry is used in the orbit determination?

Altimeter Performance

We have recommended in this report that future altimeter missions should make efforts to reduce instrument mass, volume, power and cost. TOPEX/Poseidon will use the first solid-state design altimeters. Therefore, it is critical that the T/P SWT make an assessment of the performance of the CNES Ku-band and NASA C-band solid-state altimeters.

Altimeter Range Corrections

Ionospheric range correction: The T/P SWT should compare estimates of the ionosphere range delay using a dual-frequency altimeter with models of the ionosphere based on DORIS and GPS measurements and upward looking ground observations at the calibration sites. The value of dual-frequency altimetry should be addressed in this study.

Dry tropospheric range delay: The T/P SWT should assess the accuracy of modern weather forecast models of atmospheric pressure and the dry tropospheric range delay estimate for the altimeter. Direct comparisons with ground-based measurements can be made at the calibration sites.

Sea-state bias: The T/P SWT should assess the impact of the sea state bias algorithms and estimate how well this effect can be removed from dual-frequency measurements.

Tides

The T/P SWT should build a model of ocean tides that has a precision and accuracy of better than 2-cm rms by the end of the mission. ERS-1 and ERS-2 data should be used to extend the model from 66° latitude to 82°. This model should be sufficiently accurate to permit future altimeter missions to fly in a Sun-synchronous orbit, if necessary, without the danger of errors in the solar tides producing aliases at zero and annual/sub-annual frequencies.

Waveform Processing

Routine ground processing of the raw altimeter waveforms over all surfaces is possible in near real time. An effort will be made to carry this out with the ERS-1 and TOPEX/Poseidon data. The Science Working Teams for ERS-1 and TOPEX/Poseidon should assess the value of this procedure and investigate the potential for doing this processing on the spacecraft.

Calibration Systems

TOPEX/Poseidon will address a new level of accuracy with satellite altimetry that will be necessary for global change research. This will require the development of new calibration systems to validate this accuracy. The T/P SWT should assess the value of these calibration systems for global change research. Comparisons with ERS-1 calibrations should be made in order to determine which calibration systems are required for cross-calibrating different altimeter missions.

6.2. Development Work

We have itemized several issues that can benefit satellite altimeter missions for global change research but that require some development over the next 5 years. These issues address both hardware and modeling studies and cannot be done with TOPEX/

Poseidon measurements. These include:

Reduction of Hardware Size and Cost

We have recommended a continuing development towards lightweight, low-power, inexpensive satellite instruments. For the altimeter this means studying the trade-offs of dual-frequency versus single-frequency, and considering ways to reduce the size of various subsystems as described in Section 5. The reduction in size of the nadir-pointing passive microwave radiometer, spacecraft subsystems, and onboard tracking unit must also be examined. Finally, a definitive study needs to be done that considers the benefit of merging the passive microwave and altimeter receiver antennae.

GPS Improvements

The U.S. Department of Defense has invoked the selective availability option on the GPS and it has indicated plans for implementing its anti-spoofing option when the full GPS system is on orbit. The T/P SWT needs to assess the value of the GPS data under these circumstances. An effort must be made to develop a codeless GPS receiver which would provide the same level of accuracy using the classified Y codes when anti-spoofing is turned on in 1993.

Orbit Sampling

There is a clear need for multiple satellite altimeter missions in space simultaneously to resolve the ocean meso-scale. However, there are few guidelines to dictate how the sampling patterns should be coordinated to obtain the optimum science return. Therefore, we strongly recommend the support of data assimilation and other types of studies on the utility of various altimeter sampling patterns in both single-instrument and multi-satellite configurations.

Direct Measurement of Non-Conservative Forces

The non-conservative forces on the satellite can be precisely measured using a differential accelerometer, like the French Space Three-axis Accelerometer for Research (STAR) described in Appendix E. Measurement of these forces should provide a better orbit determination at lower altitudes. The prospects of using this instrument and its impact on a mission need to be assessed and costed.

Prospects for a Low-Cost Launch

Earth observations for climate change research require multiple launches over several decades. Clearly, satellites that can be put into space with a low cost launch vehicle are desired. We recommend a conceptual design study to examine the prospects for a low cost satellite altimeter mission.

6.3. Future Missions

There are four satellite altimeter missions currently under consideration for the end of this decade. ESA's POEM-1 RA-2 is now in development and would be the logical follow-on of ERS-1 and ERS-2. The USN GFO program, also in the early stages of development, would continue the Geosat observations after a hiatus of six years sometime in the mid-1990s. A TOPEX follow-on or EOS altimeter mission is in the early stages of formulation and would continue the TOPEX/Poseidon measurements into the next decade.

The POEM-1 altimeter would continue the ERS-1 and ERS-2 observations. Accuracy and precision may be improved and performance over rough terrain, including land surfaces, will be enhanced. RA-2 will be a dual-frequency system to measure the ionosphere correction. The orbit accuracy should be an improvement over the ERS missions. It is expected that the orbit inclination will be the same as ERS-1. Therefore, this system

would continue the coverage of the polar ice sheets begun by ERS-1 and ERS-2. Coverage of the ocean by ERS-1, ERS-2, and POEM will be from a Sun-synchronous orbit and therefore could have a somewhat degraded accuracy because of potential aliasing of solar tides. It is uncertain at this time if POEM-1 will be capable of providing the necessary accuracy for measurements of the large-scale ocean circulation.

The GFO mission is not planned to meet TOPEX/Poseidon specifications for accuracy and precision. The objectives of this mission are to provide information on ocean circulation that is needed for naval operations. Therefore, it is not suitable as a TOPEX follow-on for building a long time series of observations of large-scale ocean topography for climate research. However, it will add important information about the ocean mesoscale to the TOPEX and ERS-2/POEM observations.

A TOPEX follow-on mission for the late 1990s should be developed to continue the time series of accurate measurements of the sea surface topography. The overall precision and accuracy of the measurements should be at least the same as TOPEX/Poseidon in order to ensure the measurement of the large-scale ocean circulation after TOPEX/Poseidon.

Finally, a variety of ancillary satellite measurements have been described throughout the report. Laser altimeter measurements from GLRS-A need to be carried out at the earliest opportunity to complete the description of ice sheet elevations. This instrument has the same needs for precision orbit determination as radar altimeter systems and could be flown on the same platform. Gravity field measurements need to be made from a dedicated satellite, such as ARISTOTELES, in this decade to permit the accurate estimation of the general circulation of the ocean from radar altimetry. Global ocean surface wind measurements from satellite scatterometers need to be made contemporaneously with radar altimeter measurements to provide the necessary information to study the coupling between the atmosphere and the ocean that is so important to climate prediction.

ACKNOWLEDGMENTS

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APPENDICES

APPENDIX A

RADAR ALTIMETRY OVER ICE SHEETS

There are several significant differences between radar altimeter measurements over the sloping and undulating ice surfaces compared to the relatively flat oceans. First, the 1-second along-track averaging, usually used for ocean studies, is not useful over ice. Over the ice sheets sample rates need to be at least 10 Hz. Second, the pulse-limited footprint lies at the closest area (or areas) anywhere within the beam-limited footprint. The resultant waveform shape is quite variable from one waveform to the next, reflecting the variable shape of the surface(s) within the footprints.

This variability causes not only a less accurate measurement of range, but also an ambiguity as to the location of the effective footprint on the surface within the beam-limited footprint. Crossover analysis shows that the altimeter usually measures the range to the same location on the surface on successive transits, but the precision degrades greatly as the surface slope increases. Analysis of Geosat data over Greenland has shown a measurement precision of 0.5 to 1 m in the central and flatter portions, but only 5 to 10 meters over the lower elevation western margins. Over the steeper eastern margins, only a few measurements are obtained.

One of the reasons fewer radar altimeter measurements are obtained over the steeper portions is the limitation of the altimeter tracking circuitry, which has been improved for ERS-1 and TOPEX altimeters. However, a more serious problem has arisen as the beam width has narrowed from 1.6° on Seasat and 2.0° on Geosat to 1.3° on ERS-1 and to 1.1° on TOPEX. When the surface slope is greater than 1/2 the beam width, the pulse-limited footprint lies outside the beam-limited footprint, in which case it is not possible to get a precise measurement.

Penetration of the radar signal beneath the ice sheet surface and the consequent sub-surface volume scattering produces a waveform signal consisting of a surface return followed by the volume scattering return (Ridley and Partington, 1988). The strength of the volume scattering relative to the surface return varies with the characteristics of the firn near the surface. This effect decreases the ability to accurately and consistently determine the surface return, but can be mostly accounted for with proper retracking algorithms. However, the penetration is frequency dependent and frequencies lower than 13 GHz are likely to compound this problem.

APPENDIX B

THE CNES SOLID-STATE ALTIMETER

In 1982, CNES decided to study a new altimeter concept, based on solid-state technology and onboard processing, which would be more easily accommodated on small satellites, or as a "passenger" on non-dedicated missions. A single frequency was chosen, assuming a correction of the ionospheric error by use of the DORIS dual-frequency measurements. A breadboard was built in-house, and a first flight model (Poseidon) was delivered in 1990. It is now integrated on the TOPEX/Poseidon satellite. All simulations and measured parameters confirm the design goals (Raizonville et al., 1991).

The main characteristics of this altimeter are low mass and power and an increase in reliability and long-term stability. The mass of the CNES altimeter is 23 kg without redundancies or antennae. The power demand is 49 W. These values are the result of highly integrated technologies (pulse compression with acoustic lines) and the solid-state transmitter. The initial goal for the altimeter output power was 2 W. This goal has been surpassed; 5.5 W have been obtained in the TOPEX/Poseidon flight model and 10 W would be possible using available parts. These values are below the 20-W NASA TOPEX Ku-band power tube altimeter; however, there is no impact on either the accuracy or the precision. For most ocean echoes, the backscatter return signal is much stronger than the thermal noise. The reduction in pulse power will only be significant in the case of very heavy rain attenuation, which occurs less than 1% of the time.

To decrease the telemetry volume (by about a factor of 8) and reduce the interface constraints, onboard processing is an important characteristic of the CNES altimeter. The tracking and the estimation functions are shared. The tracking function requires a relative agility of the range and power loops to maintain lock on the return signal in case of height acceleration or power variation, which usually results in reduced precision.

The estimation function corrects for the tracker errors and performs a Maximum-Likelihood Estimation (MLE) of the useful parameters (height, power, slope). It was found that this onboard estimation, in spite of the microprocessor limitations, does not degrade the accuracy, and degrades the precision by only a few percent compared to the optimal MLE algorithm. By-products of the estimation are the noise level and the antenna mispointing angle, which may be used to correct the height estimation, if no better satellite data are available.

The Poseidon solid-state altimeter. (Figure courtesy of CNES.)

The tracking efficiency gives a short acquisition time, typically 2 seconds, and makes the altimeter insensitive to acceleration. Modification of the onboard estimator algorithms and data are possible by upload, for instance, if the calibration shows that the actual waveform shape is slightly different from the assumed one.

The typical precision of the altimeter is 2.5 cm for 1-s averaging. Since there is no effect of dynamic errors (acceleration, tracker filtering) on the estimation, the spatial resolution is only limited by the geometrical filtering of the pulse/sea interface (about 1500 m). The slowly varying errors are estimated to be 2 cm (bias, hardware and antenna mispointing), a part of which may be removed by laser calibration.

For future missions, if the telemetry rate is not a constraint, it should be possible to transmit all waveforms for full processing on the ground. But, unless a very complex (only achievable by the ground system computers) and efficient algorithm is found to correct for sea-state effects, the baseline will be to limit the full-rate telemetry for calibration purposes, and to use only look-up tables in the ground system for possible residual effects of Significant Wave Height (SWH). Consistent progress in microprocessor technology would also make it possible to improve the efficiency of the onboard estimation, if necessary.

There are four different methods for estimating the ionospheric range delay. First of all there is the modeling approach already used for GEOSAT and ERS-1. The correction used in the GEOSAT GDRs is based on a method using ground-based dual-frequency measurements from GPS observatories which are fitted with a global model. These estimates are only valid to about 50% and insufficient for precision altimetry given the 30-cm dynamic range of the ionospheric correction during periods of high solar flux. In the ERS-1 GDRs, the ionospheric range delay is obtained using a semi-empirical global model which is based on historical data and is valid to about 70% (Llewelyn and Bent, 1973).

The other methods use direct measurements. The definitive measurement can be made using a dual-frequency altimeter as is planned for TOPEX/Poseidon. However, dual-frequency altimeters are costly in terms of both weight and power. Consequently, alternative techniques are being considered for future missions. One approach would use the dual-frequency measurements from the onboard DORIS tracking system or from the GPS satellites tracking systems. Neither of these measurements are coincident with the radar signal path; some type of modeling effort would be needed to solve for the nadir path-length delay. Finally, sounding measurements of the ionosphere to the peak of the electron density profile at nadir have been carried out from spacecraft. These measurements would also require some level of modeling. In the next few years, experience will be gained with dual-frequency altim-

etry and modeling with tracking system measurements using observations from TOPEX/Poseidon, and an assessment of ionosondes will be conducted.

Dual-Frequency Altimetry

The approach taken by TOPEX/Poseidon is to make range measurements at two frequencies: 13.6 GHz (Ku-band) and 5.3 GHz (C-band). These two measurements can be used to derive the range delay and the total electron content, because the range delay is different at these two frequencies. The error in the range delay estimate is about 2 cm and is primarily caused by the noise in the altimeter measurement. Therefore, this error can be substantially reduced by along-track averaging. Other possible errors are connected with unmodeled effects that are frequency-dependent. For example, electromagnetic bias, which appears to vary with frequency, is one such possible error. Such errors cannot be reduced by along-track averaging.

DORIS Tracking Measurements

The satellite tracking data collected by the DORIS receiver can also be used to estimate the ionospheric range delay because the data are received at two frequencies (401.25 MHz and 2036.25 MHz). With this system, only a differential total electron content (TEC) along the tracking beacon line-of-sight can be measured, because DORIS measures the range change over the count interval and not an absolute value of

range. Furthermore, DORIS line-of-sight observations are not boresighted with the altimeter pulse and must be mapped to the altimeter nadir using a model.

Over a unique visibility pass the initial TEC cannot be solved, but this parameter is solved by applying continuity constraints between the beacon's visibility areas, and then no external measurements or model are required. The residual errors will probably have a finite, low wavenumber component that cannot be reduced by along-track averaging. Nevertheless, the densely populated global network of over 40 DORIS ground stations makes this approach an attractive alternative to the dual-frequency altimeter approach.

The exact extent of the utility of the DORIS approach has to be demonstrated by comparison with the dual-frequency altimeter measurement on TOPEX/Poseidon. Initial computations with DORIS measurements from the SPOT-2 spacecraft have been very promising.

GPS Tracking Measurements

The use of GPS tracking data to determine the total electron content can be accomplished if a global network of relatively densely populated ground stations is available. Similar to the DORIS measurements, these observations are not boresighted with the altimeter pulse direction. When available, the difference of high-precision code (P-code) pseudo range measurements at the L_1 and L_2 frequencies can be used to determine the TEC along the line-of-sight of the GPS signal. The estimates of TEC can be further refined if necessary by using the L_1 and L_2 carrier phase measurements.

Use of the more commonly available phase measurements alone is equivalent to the computation with DORIS measurements. These line-of-sight measurements can be mapped to the altimeter nadir through the
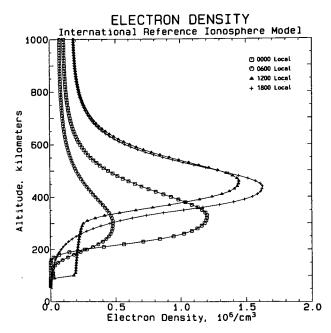
use of an ionosphere model. GPS is a very precise tool for measuring the ionosphere in areas where suitable data are available. Comparisons between the dual-frequency altimeter measurement and models based on DORIS or GPS will be possible with TOPEX/Poseidon observations next year.

Ionosondes

Another potential approach is the use of an ionospheric sounding device known as an ionosonde or topside sounder. This instrument profiles the upper ionosphere density between the satellite and the altitude (~200 to 300 km) of the electron density peak. This is a low-risk technology with proven spaceflight experience (e.g., the Canadian Alouette and ISIS projects).

An ionosonde shares the advantage of the dual-frequency altimeter system by measuring the ionosphere along the altimeter line-of-sight. The advantage of the ionosonde is that, in conjunction with a single-frequency altimeter, it may offer a lower system cost than a dual-frequency altimeter. An added benefit for ionospheric science is that an ionosonde will yield data on the structure of the upper ionosphere, which is not provided by the integrated TEC measured by a dual-frequency altimeter system.

The primary disadvantage of the ionosonde is that the electron density from below the electron peak (~35% TEC) is not measured directly, and must be estimated from the measured peak density and model of the lower ionosphere profile. This lower region is subject to an important variability associated with thermospheric coupling and magnetospheric effects. Furthermore, in regions of large horizontal ionospheric gradients, such as the magnetic poles, the lower frequencies of the ionosonde (1 to 20 MHz) are subject to greater refraction than the microwave radar, and will not match exactly the altimeter ray-path.

ELECTRON DENSITY
International Reference Ionosphere Model

Sample ionosphere profiles based on the International Reference Ionosphere (IRI) model (Bilitza, 1990). This simulation is for a location at 0° latitude and 180° longitude, during a period near maximum in the solar cycle. Diurnal variability is illustrated by the four curves at the local times indicated. A topside sounder would measure the ionosphere profile from the satellite altitude to the electron density peak. The ionosphere below the peak will need to be estimated from a model such as IRI, in order to compute the total electron content (TEC). (Figure courtesy of G. Lagerloef, SAIC.)

value of dual-frequency altimetry. We recommend that options concerning dual-frequency altimetry should be considered in order to reduce the weight, power and cost factors of precision radar altimeters. We suggest that an aggressive approach to ionospheric modeling be taken using ionosonde or dual-frequency tracking measurements in place of dual-frequency altimetry.

Preliminary estimates indicate that a TEC measurement uncertainty of <5% is needed to maintain an altimeter range correction uncertainty of 1 to 2 cm during peak solar activity periods, and less at other times. It is very likely that an ionosonde will be able to meet this requirement during most conditions, and a feasibility study to quantify these errors is underway. A combination of an ionosonde with DORIS and/or GPS may offer the equivalent ionospheric range correction accuracy as a dual-frequency altimeter system.

Conclusion

In the next few years, spaceflight experience will be gained for a variety of methods to estimate the radar altimeter ionospheric refraction delay. We will assess the
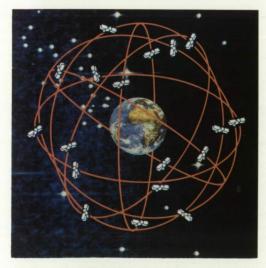
SATELLITE TRACKING SYSTEMS

During the mid-1990s, four different tracking systems should be available to provide tracking data for future altimeter flight systems. These include range measurements from the ground-based laser ranging system, range and range-rate tracking by the PRARE system, Doppler or range-rate measurements from the DORIS system, and range and carrier phase measurements from the Navigation Satellite for Timing and Ranging (NAVSTAR) GPS satellites. Geodetic and oceanographic applications of future altimetric range data dictate real-time positioning of the platform with an accuracy of better than 5 m radially, and better than a few cm in the radial component for the final geophysical data record.

Global Positioning System (GPS)

The Global Positioning System (GPS) is a satellite-based navigation system designed to provide continuous all-weather

A schematic of the GPS distribution of satellites.

navigation to appropriately equipped users on a worldwide basis. The operational system consists of 21 satellites (plus 3 active spares) 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, Pseudo-Random Noise (PRN) signals on two coherent L-band frequencies (L_1, L_2) are transmitted continuously. A conventional receiver decodes the transmitted signal to obtain GPS orbit elements, time calibration data, and measurement data.

TOPEX/Poseidon will carry an experimental GPS receiver onboard the satellite in 1992 that should demonstrate the technical feasibility of meeting future altimetric mission's post-processing accuracy requirements of 10-cm rms in the radial component. This receiver will have the capability to generate an onboard ephemeris accurate to about 10 m for the host satellite by using P-code pseudo range.

Ground processing of differential carrier phase, range and delta range between TOPEX/Poseidon, the GPS satellites, and six ground stations may be able to provide sub-decimeter altitude accuracy. The optimum data processing strategy is a combination of dynamic and geometric techniques referred to as the reduced dynamic technique. This approach promises to yield maximum accu-
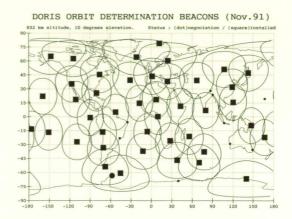
racy for both TOPEX/Poseidon and future missions, as well. It will be important however to continue to improve dynamical model ingredients such as the gravity field.

A concern for future missions is that anti-spoofing (AS) will be implemented for the GPS Block II Constellation after it is declared operational. This means that the P-code is encrypted (then called Y-code) and flight receivers not properly equipped will not have access to it. Conventional receivers could still obtain coarse acquisition (CA) code pseudo-range and L_1 carrier phase but would not have access to L_2 pseudo-range, which is necessary for ionospheric corrections. Current thinking is that the accuracy potential for this situation is between 20-cm and 1-m rms.

Data from the GPS experiment on TOPEX/Poseidon will allow an assessment of this tracking scenario. A possible solution to the problem of AS is the development of a codeless flight receiver that would correlate the L_1 and L_2 Y-code in order to correct for the ionosphere and would reconstruct carrier-phase data. Because of these questions, the future of unclassified GPS flight hardware for high-orbit-accuracy applications is somewhat uncertain.

Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

The Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system was designed and developed by CNES (Centre National d'Etudes Spatiales), the GRGS (Groupe de Recherches de Geodesie Spatiale) and the IGN (the French National Geographic Institute). The DORIS tracking system provides satellite range-rate measurements with a design precision of about 0.3 mm/s. Currently there are about 40 stations in the DORIS system, providing a 60-65% coverage. The complete system will consist of over 50 stations that will be well distributed over the entire globe. The DORIS

DORIS ORBIT DETERMINATION BEACONS (Nov.91)

832 km altitude, 10 degrees elevation.   Status : (dot)negociation / (square)installed

DORIS tracking sites. (Figure courtesy of CNES.)

system will provide about 75-80% global tracking coverage of satellite orbits above 800 km in altitude.

The DORIS system measures one-way range-rate from the ground station to the satellite. The ground stations transmit at frequencies of 2 GHz and 400 MHz. The separation of the two transmitting frequencies makes it possible to reduce the ionospheric effect to around the centimeter level and tropospheric refraction is modeled using surface meteorological data from the ground stations which are directly transmitted to the satellite.

The control center collects all of the measurements made by the satellite and the ground stations. It monitors the onboard receiver and the ground station beacons. This center plans all commands transmitted by the satellite and designs the remote loading of data.

The DORIS tracking system is currently used to track the French SPOT-2 satellite and is scheduled to fly on TOPEX/Poseidon as well as on follow-on SPOT satellites (SPOT-3, SPOT-4). The beacon network shall be maintained throughout the 1990s. DORIS will be a well-tested operational system and a strong candidate to provide sub-decimeter orbits for future altimetric missions.

Precise Range and Range-rate Equipment (PRARE)

The Precise Range and Range-rate Equipment (PRARE) is an active, two-way, dual-frequency (S- and X-band) tracking system developed by the Deutsches Geodaetisches Forschungsinstitut and the University of Stuttgart in Germany and was launched, but failed, onboard ERS-1.
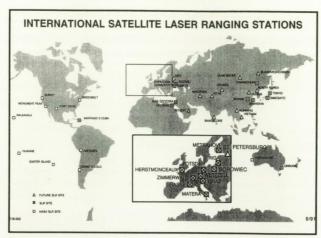
The PRARE system consists of three components: the space segment onboard the spacecraft; the ground segment with a network of ground tracking stations and the control segment with the master ground station for control operations; data transfer to and from the spacecraft payload; and pre-processing of the tracking data. The signals are generated onboard the satellite and are transmitted at 2 GHz and 8 GHz to the ground stations.

The dual-frequency PRARE signal allows for ionospheric refraction corrections. Surface meteorological measurements at the stations provide tropospheric (both wet and dry) refraction corrections to the range and range-rate. Measurement precision is expected to be around 2-cm rms for X-band range and 0.1 mm/s for X-band range-rate (Doppler) for 1- and 30-second integration times, respectively.

Given a proper distribution of ground stations, PRARE is adequate to produce sub-decimeter orbit accuracy for low-Earth-orbiting satellites. PRARE is anticipated to fly on ERS-2 and future ESA satellites requiring precise orbits. Hence, it is expected to be in operation for a number of years and should be a viable candidate for the precise tracking system on future altimetric missions.

Satellite Laser Ranging (SLR)

A global system of laser stations provides the potential for orbit determination

SLR distribution of stations. (Figure courtesy of Crustal Dynamics Project Office, NASA/GSFC.)

accuracy of a few centimeters. Currently, there are two major arrays of laser tracking stations—one in North America and one in Europe, and with an adequate cluster in the South Pacific. Plans for adding the Chinese SLR network and SLR systems in Russia, along with stations in Africa, promises a well balanced network for supporting SLR-based missions.

The SLR system is critical to comparing the results from SLR data sets collected over several decades. It is the only technique with a proven capability for determining the satellite orbit in a well-defined geocentric reference system. The fact that the space segment of SLR systems cannot fail, provides a unique reliability for the tracking system, as was proven on ERS-1. Finally, regional SLR tracking will be required for altimeter height measurement verification; hence, future altimeter spacecraft should carry a laser retroreflector.

These devices are lightweight (ounces), inexpensive (on the order of $1000 each) and do not interfere with the other components of the measurement system. The attendant requirement is that an adequate global network be maintained to support the precision orbit determination requirements.

Summary

Each of the tracking systems described here has problems of inadequate global coverage to overcome. GPS will achieve global coverage as more spacecraft are launched but the problems associated with data denial remain to be solved. The number of DORIS ground stations is growing steadily and will yield nearly continuous coverage. The number of PRARE and SLR stations will be increased as well, although it is not known how extensive these networks will become.

Each of the tracking systems described here has the potential to produce orbits accurate to a few centimeters for future altimeter missions. However, the capability to meet the SLR accuracy and geocentric height control has not been demonstrated for either of the radiometric systems (DORIS, PRARE, and GPS). In-flight performance characteristics of DORIS and GPS will be determined from TOPEX/Poseidon measurements.

DIFFERENTIAL ACCELEROMETERS

One of the possible limitations in performing precise altimetry in low (~ 800 km) orbits comes from mismodeling of surface forces : drag or solar pressure, either direct or reflected from the Earth. Even using the geometrical properties and attitude of the spacecraft, the uncertainty on the acting forces is a limiting factor for a precise orbit determination. The fast variations linked to solar activity or Earth albedo are especially damaging. Empirical adjustment may partly overcome this difficulty. One realistic alternative is to measure these surface forces with an onboard instrument.

There is an instrument that can measure the surface forces on a spacecraft that has been satellite tested. Its principle is to measure the differential accelerations between the external surface and a small ball placed at the center of a spherical shell close to the center of mass. The accelerations are measured by capacitive three-axis detectors. Active electrodes will maintain the proof mass at the center.

The first version of this instrument was called CACTUS and built by the French Office National d'Etudes et de Recherches Aerospatiales (ONERA). It was flown on the CNES CASTOR satellite that was launched in 1975 and achieved a 2 1/2-year mission. The measured precision was 10^{-10} m/s^2. More recently, ONERA built a miniaturized and upgraded version called the Space Three-Axis Accelerometer for Research (STAR). This instrument is available and is a strong candidate for future flights.

The Space Three-axis Accelerometer for Research. (Figure courtesy of CNES.)

A constraint on the spacecraft is that the center of the device should be as close as possible to the satellite's center of mass. Instrument calibration is performed on the ground. The remaining calibration error is less than 3 parts per million and may be corrected either by inflight calibration (displacement of a proof mass) or by external calibration. The inertial accelerations, such as centrifugal acceleration, should be either very precisely determined or minimized to avoid saturation of the accelerometer. In practice, this can be achieved by displacing a small mass to maintain the center of mass of the satellite as close as possible to the accelerometer (this is the solution used for STAR).

To give orders of magnitude in the SPOT2/Geosat range of altitude, the perturbing accelerations are typically:

• For drag between 10^{-7} and 5×10^{-9} m/s^2 : During periods of strong geomagnetic activity, perturbations of the drag can induce orbit errors of several meters in a few hours.

- For direct and reflected parts of the solar pressure, between 10^{-8} and 10^{-9} m/s^2 : Their integrated effect tends to generate orbit errors having very long periods.

We have mentioned here the ultimate accuracy that can be obtained by an accelerometer. It is, however, worth mentioning that without drastic efforts, such a device is able to measure the non-gravitational forces with a 1-percent accuracy in the three directions.

STAR characteristics

Dynamic Range	3×10^{-5} to 3×10^{-10}	m/s^2
Resolution	$\sim 10^{-10}$	m/s^2
Rate of Measurement	2	per sec
Volume	1	dm^3
Power	1	W
Mass	2	kg

GLOSSARY

ARISTOTELES	European Space Agency Gravity Mapping Mission
AS	Anti-Spoofing on GPS transmissions
C/A	Coarse/Acquisition GPS signal structure
CNES	Centre National d'Etudes Spatiales
DMSP	Defense Meteorological Satellite Program
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
ENSO	El Niño Southern Oscillation
EOS	Earth Observing System
EPOP	European Polar Operations Platform
ERS-1, ERS-2	ESA Remote Sensing Satellites
ESA	European Space Agency
GCRP	Global Change Research Program
GDR	Geophysical Data Record
Geos-3	NASA Geodetic Satellite Mission
Geosat	U.S. Navy Geodetic Satellite
GFO	Geosat Follow-On
GHz	GigaHertz
GLRS-A	Altimeter part of Geodynamics Laser Ranging System
GPS	Global Positioning System
GRGS	Groupe de Recherches de Geodesie Spatiale
GSFC	Goddard Space Flight Center
IPCC	International Panel on Climate Change
IERS	International Earth Reference System
IGN	Institut Géographique National
IR	Passive Infrared Radiometer
MHz	MegaHertz
MLE	Maximum Likelihood Estimation
MOLA	Mars Observer Laser Altimeter
MR	Passive Microwave Radiometer
MTPE	Mission To Planet Earth
NASA	National Aeronautics and Space Administration
NAVSTAR	Navigation Satellite Timing and Ranging
NOAA	National Oceanic and Atmospheric Administration
P-Code	GPS precision transmission code
POD	Precision Orbit Determination
POEM	ESA Polar Orbit Earth-observation Mission
PRARE	Precise Range and Range-rate Equipment
PRN	Pseudo-Random Noise
RA-2	ESA POEM altimeter
RMS	Root-Mean-Square

SA	Selective Availability on GPS transmissions
SCAT	Radar Scatterometer
Seasat	NASA Ocean Remote Sensing Satellite
SLR	Satellite Laser Ranging
SPOT	French Satellite Pour l'Observation de la Terre
STAR	Space Three-Axis Accelerometer for Research
SWH	Significant Wave Height
TEC	Total Electron Content
TOPEX/Poseidon	NASA/CNES Ocean Topography Experiment
T/P SWT	TOPEX/Poseidon Science Working Team
TWT	Traveling Wave Tube
U.K.	United Kingdom
U.S.	United States
USN	United States Navy
VLBI	Very Long Baseline Interferometry
WOCE	World Ocean Circulation Experiment
WVR	Water Vapor Radiometer