SP-1196 (9)

REPORTS FOR ASSESSMENT

THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Topography Mission

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THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Topography Mission

ESA SP-1196 (9) – The Nine Candidate Earth Explorer Missions –
TOPOGRAPHY MISSION

Report prepared by: Earth Sciences Division
Coordinator: Chris J. Readings

Earth Observation Preparatory Programme
Coordinator: Mike L. Reynolds

Cover: Richard Francis & Carel Haakman

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Contents

1. Introduction

For the post 2000 time frame two general classes of Earth Observation missions have been identified to address user requirements, namely:

> **Earth Explorer Missions** – these are research/demonstration missions with the emphasis on advancing understanding of the different Earth system processes. The demonstration of specific new observing techniques would also fall under this category.
>
> **Earth Watch Missions** – these are pre-operational missions addressing the requirements of specific Earth observation application areas. The responsibility for this type of mission would eventually be transferred to operational (European) entities and the private sector.

Nine Earth Explorer missions have been identified as potential candidates for Phase A study. For each of these candidate missions Reports for Assessment have been produced.

This particular Report for Assessment addresses the Earth Explorer Topography Mission. It has been prepared by the Topography Mission Working Group (TMWG). The four (external non-ESA) members of this particular Mission Working Group are Duncan Wingham (Mullard Space Science Laboratory, London, UK), Pierre De Mey (Centre National de la Recherche Scientifique, Toulouse, France), Philip Hartl (Institut für Navigation, Stuttgart, Germany), and Stein Sandven (Nansen Environmental and Remote Sensing Center, Bergen, Norway). They were supported by members of the Agency who advised on technical aspects and took the lead in drafting the technical/programmatics chapters. This Report for Assessment, together with those for the other eight candidate Earth Explorer missions, is being circulated amongst the Earth Observation research community in anticipation of a Workshop which will take place in Granada (Spain) from 29-31 May 1996.

The Earth Explorer Topography Mission is intended to focus on four aspects of the world climate system, i.e. the oceans, the sea ice, the ice shelves and the ice sheets. These, in influencing trends in the planetary albedo, the ocean thermohaline circulation, and the hydrological cycle, play a fundamental role in the climate and its impact over tens to hundreds of years. Currently these systems are poorly represented in coupled climate models. To achieve its objectives the mission would measure sea ice thickness and roughness, permitting the determination of a sea ice mass and freshwater flux climatology, and simultaneously measure the high latitude ocean variability, exploring coupled ocean-ice-atmosphere interactions. In addition, seasonal elevation variations of ice sheet margins, ice shelves and high latitude glaciers will be monitored, closing the cryospheric component of the hydrological budget. The mission will also provide elevations of the land surface and, for the first time, the remote gauging of the worlds rivers.

All the Reports for Assessment follow a common general structure comprising seven chapters. They each start by addressing the scientific justification for a particular mission and move on to detail its specific objectives. This is followed by a discussion of the specification of observation requirements and a listing of the various mission elements required to satisfy the observational requirements. Then consideration is given to the implications of meeting the observational requirements in terms of both the space and ground segment as well as requisite advances in scientific algorithms and processing/assimilation techniques. Finally programmatic aspects are considered.

2. Background and Scientific Justification

The topography of the Earth's land, ice and ocean surface is a boundary condition of many processes acting at the base of the atmosphere, and is also the surface expression of forces acting within the bodies of the solid Earth, the oceans and the ice sheets. It is also the surface on which mankind lives and works, and knowledge of it is essential to many economic activities. This chapter, reviews, under the headings of the cryosphere, the oceans and the land, its importance to many scientific disciplines and human activities. Only limited references to recent publications and reports are provided with the text.

2.1. The Scientific and Practical Importance of the Earth's Topography

2.1.1. The Cryosphere

Sea Ice

Sea ice covers large areas of the oceans at high latitudes and plays a crucial role in many physical and biological processes in these areas. The presence of sea ice substantially modifies the air-sea heat and momentum exchanges in polar regions, and hence can play a major role in high latitude climate sensitivity. In the Northern Hemisphere the total area of sea ice varies from a minimum of about 8×10^6 km^2 in September to more than 14×10^6 km^2 in March. In the Southern Hemisphere a maximum ice area of about 20×106 km^2 is found in September, while a minimum of 4×10^6 km^2 is found in March. (In comparison the area of Canada is about 10×10^6 km^2)

Sea ice is formed by freezing of the ocean surface primarily in winter time when low air temperatures are maintained over days and weeks. The freezing point of the ocean is about -1.8° C, depending on the salinity, and the most intense ice freezing occurs when the air temperatures is below -20° C. Icepack, which is typically 2-4 m thick and covers 100% of the ice areas, acts as an insulator which limits strong heat flux from ocean to atmosphere. When the icepack opens up and the ocean surface is exposed to low air temperatures, the heat flux from ocean to atmosphere is of order 100 W m^{-2}, and can be as high as 1000 W m^{-2}. Sea ice advection, in combination with ocean currents, plays an important role in the meridional transport of heat and freshwater, and is an important mechanism influencing the global oceanic thermohaline circulation. The high albedo of sea ice has significant impact on global temperature via its reflection of solar radiation, prohibiting heat uptake by the ocean. Moreover, the high albedo of sea ice has a significant positive feedback on global temperature change, in that, should temperatures lower and more ice form, increased solar radiation will be reflected and temperatures fall still further.

Sea ice density is always lower than the sea water density, allowing it to float on the sea surface. Typical values range from 880 to 910 kg m^{-3}, with the difference depending primarily on its air and salt content. The density increases with increase in salinity and decreases with increase in porosity. Characteristic salinity is 12-15 psu (practical salinity unit) for newly formed ice, 4-5 psu for first year ice, and near 0 psu at the top of multiyear ice.

Sea ice has a great environmental significance at a range of temporal and spatial scales. On the global scale, most general circulation models (GCMs) expect that greenhouse warming will be amplified in the high-latitudes, especially in the Arctic (e.g. Mitchell et al., 1995). Sea ice is the predominant climate-related feature in the Arctic, and the climate modelling community considers a reduction in Northern Hemisphere sea ice as one of the most probable changes resulting from increasing greenhouse gas concentrations (Barron, 1995). Energy and mass exchanges associated with the growth, movement and decay of the seasonal ice cover have important feedbacks on the global climate system. The relatively fast response time of sea ice to changes in temperature suggests that a reduction in the Arctic sea ice cover could be the first evidence of global greenhouse warming. On regional- and sub-regional scales, the sea ice cover is important oceanographically and climatically, for example, its role in deep-water formation in the Greenland Sea (Johannessen et al., 1991) and the Weddell Sea.

The seasonal ice zones in both hemispheres are important areas in marine biology because of high level of affluent nutrients and high light level in the summer season. Microbiota, macrobiota, marine birds and mammals depend on sea ice for part or all of their lives. The growth and dynamics of sea ice also affect the rates and types of biological processes related to the carbon cycle, and the sequestration and outgassing of carbon dioxide. Sea ice also absorbs, advects and delays transport of atmospheric trace gases and pollutants. In the Arctic the delay can be up to five years and advection over 1000 km.

Sea ice cover is also of great practical importance, affecting fisheries, offshore activities and transport operations. Twenty percent of the world's fish catch, more than 12 million tones per year, is landed from the northeast Atlantic Ocean, including the Barents Sea and other Arctic ice edge regions. The occurrence of fish is dependent on many factors including over fishing, but a major factor is the primary productivity of northern waters. Sea transport at high latitudes is severely hampered by the presence of sea ice. Expensive icebreakers and ice-strengthened vessels are required to support this transport. Of importance to transport operations and offshore oil exploration and development is near-real-time information on large-scale characteristics (e.g., ice motion and ice edge position) and meso- and sub-meso-scale characteristics (e.g., ice type and ice deformation). Accordingly, timely ice monitoring at a range of spatial and temporal scales is a practical necessity.

Land Ice

The Earth's climate over the past 100,000 years has been dominated by coupled fluctuations in temperature, atmospheric carbon dioxide, large ice masses and sea level. There is growing evidence from ice cores that in the past, large and sustained changes in average atmospheric temperature have occurred on time scales of decades . The cause of these changes is a matter of debate. It is possible that they occurred as a result of large freshwater discharge from the Northern Hemisphere ice sheets (Broeckner 1994), but it is also possible the ocean circulation itself may be capable of rapid, sustained changes. The history of total ice mass reduction from the last glacial maximum is reasonably well established in the Northern and Southern Hemispheres, largely through relative sea level curves (Peltier 1988; Nakada & Lambeck 1988), although regional details are very unclear, particularly in the Southern Hemisphere. The surface warming marking the Holocene is now reaching the lower parts of the Greenland Ice Sheet, while in Antarctica much of the bed remains essentially unchanged.

The mass balance and contribution to the observed 20th century sea level rise of 1.6 mm/yr^{-1} of the ice sheets of Antarctica and Greenland is very uncertain, and almost nothing is known as to the regional distribution of the balances. In a recent survey, Jacobs (1992) attempted to reconcile the various estimates of the mass balance of the Antarctic ice sheet. He suggested that the data supported the case that the grounded ice may be growing at a rate of 40 to 400 Gt yr^{-1} (-0.1 to -1.1 mm yr^{-1} of sea level rise). On the other hand, sea level rise over the last century indicates a shrinking of Antarctica by 162 Gt yr^{-1}. Experimental evidence from Greenland indicate at least some drainage basins are in balance. However, the data is very sparse (see e.g. Wingham 1995) and could support an imbalance of 80 Gt yr^{-1}. At present, these uncertainties are the largest uncertainties in determining the causes of the present rise in eustatic sea level.

In the event of climate warming, various estimates have also been compiled of the contribution of Antarctica and Greenland over the next century to eustatic sea level. Atmospheric warming is expected to increase accumulation over the Antarctic sheet, by around -0.2 mm yr^{-1} of sea level equivalent (Oerlemans 1993). Approximately half of the mass loss from the Greenland Ice Sheet is through surface ablation, and it is therefore particularly exposed to the effects of warming (Ambach 1993). What data exist indicate a rise in temperature of 2 K may result in an increased contribution to sea level rise of 0.2 mm yr^{-1}. While these two estimates largely cancel, they are uncertain to at least +/- 0.1 mm yr^{-1} (Oerlemans 1993). In addition, the estimates take no account of how warming-induced changes in atmospheric circulation may effect ice sheet precipitation, which is now known to be strongly dependent on storm tracks.

Warming of the oceans will substantially increase the melt rate from the ice shelves. An uncertainty of 300 Gt yr^{-1} (0.8 mm yr^{-1}) exists (Jacobs et al. 1985) in the rate of bottom melting from the ice shelves. The ice shelves of the Antarctic peninsula have seen significant retreat this century (Doake and Vaughan, 1991) which may have consequences for the rate of flow of the grounded ice, and hence eustatic sea level. The very substantial uncertainties in the physics of the ocean/ice shelf/ice sheet interaction (MacAyeal 1992) result in the wide range of the estimates.

Melting from the under surface of ice shelves accounts for 10% of oceanic heat loss south of 60° S and perhaps 2 Sv of the 12 Sv of bottom water formed on the continental shelf. Recent results from coupled ocean/atmosphere circulation models indicate that the Southern Ocean could play an important role in 'short circuiting' southward heat flow for century to millennium time scales; changes in the cold, dense bottom water formed from the shelves and in the Weddell Sea may impact this vertically unstable circulation.

The reservoir volume of small ice masses and glaciers is 0.5 m of sea level equivalent. While this is very much smaller than that of the large Ice Sheets of Antarctica and Greenland, these ice masses are considerably more dynamic. The retreat over the 20th century of small ice caps and glaciers is estimated to have contributed 0.4 mm yr^{-1} to the 20th century rise in eustatic sea level. Much of the ice volume lies in the sub- or high Arctic glaciers and ice bodies, a region where the effects of global warming is expected to be amplified. Global warming is expected to have a very significant impact on the volume of these ice bodies, resulting in a increase in the rate of sea level rise of 1 mm yr^{-1} K^{-1}.

2.1.2. The Oceans

To improve our knowledge and prediction capabilities of the world climate at seasonal, interannual, and longer time scales, it is essential that ocean circulation processes be well observed, understood, and simulated. Ocean thermodynamics has a stabilising role on climate. The ocean and atmosphere together are responsible for the meridional heat transfers (e.g. Bryan, 1991). Mechanical energy, mass and heat are exchanged at their interface and couple the whole system. Therefore global, repeated observations of the ocean are a critical element of the research on climate dynamics and on perturbations of the coupled atmosphere/ocean system. The practical applications of this research, through improved ocean circulation prediction, include the economic effects on agriculture and fishing (El Niño, for example), and the consequences of sea-level changes in coastal, populated lowlands such as most of the coasts of Europe.

The effects of high-latitude ocean, land and ice on seasonal to interannual climate predictability are only now being studied. These studies should complement the active ongoing research on ENSO (El Niño/Southern Oscillation) and predictability in the tropics. Since the coverage and characteristics of sea-ice change seasonally, large intra-annual and sometimes interannual variations in the energy, heat and freshwater budgets of the upper ocean are observed; these processes impact the large-scale thermohaline circulation as a whole. On the other hand, mesoscale high-latitude eddies and currents move heat around, and significantly contribute to the modification of sea-ice distribution, which has an important effect of climate through change of albedo.

Ocean science can improve climate prediction and lead to significant applications provided that a long-term, integrated approach is followed:

- The approach must rely on an emerging but explicit synergy between research (WOCE, TOGA, CLIVAR and follow-ons) and applied/operational (GOOS, GCOS) programmes, and between spaceborne and in-situ measurements. As far as the ocean is concerned, the CLIVAR and GOOS objectives can serve as a reference in the time frame considered here. They explicitly couple the shorter-term and longer-term (decadal, centennial) variability which has been shown to exist in the ocean.

- As in the atmosphere, the 'best' description of the ocean (as well as for forecasting) can only be attained by simultaneous use of observations and numerical models via data assimilation methods. Observing systems must be explicitly designed for the ultimate use of data in models. Observations must be available over a long time with no data gaps. Data, once taken, become a valuable part of the climate record; if lost, they become unavailable to the climate record and can never be retaken. In addition, long runs (10 years or more) of data assimilation are necessary to provide access to the model errors.

In addition to climate studies, there are many reasons why a continued and significantly better knowledge of ocean circulation per se is to be sought. The ocean is a turbulent, limited-predictability system. Therefore observations of the ocean will always be necessary. An estimation of the ocean currents, temperatures, nutrients, and chemical tracers throughout the water column is essential for biochemical and physical oceanography. For instance, the knowledge of near-surface currents can help improve air/sea interface parameterisations as well as transoceanic routing and oil pollution control; ocean mesoscale temperature changes are critical for military applications as well as for industrial fishing. In such quasi-real-time applications, observations stay 'fresh' for up to a few days, given the longer time scales in the ocean compared to the atmosphere.

2.1.3. The Land

The land surface is the boundary between the atmosphere and the solid Earth. The shape of this surface, the topography, has a controlling or important role in physical and chemical processes acting on or at the surface. The topography is supported by forces acting in or on the continental lithosphere, and therefore also provides an important clue as to the origin and magnitude of these forces. Its influence on surface precipitation, temperature, wind and insolation make it a dominant factor in vegetation species distribution and growth. Through its control of water flow it influences the drainage and surface transport of sediments, chemicals and other materials. It is also a major factor in the distribution of agriculture, human settlement, transport and communications. The digital representation of topography and its isolation as a variable of particular importance, arose historically for the interpretation of Earth gravity, and in global climate modelling, in which the representation of Northern Hemisphere topography resulted in significant improvements in atmospheric dynamics.

Topographic data and the information derived from it are generally regarded as critical components of land process studies and global change modelling activities. The modelling of atmospheric dynamics over the land surface requires topography at scales from 1-10,000 km. At the largest scale, the topography of the Earth is a major source of drag on the atmosphere and responsible for some 50% of the exchange of angular momentum between the atmosphere and the Earth. It has a major influence on precipitation and its distribution over the land surface of North and South America, Africa, Northern Europe and South East Asia. To distinguish the effects of lateral density variations in the mantle and lithosphere in the Earth's gravity field, accurate topography on scales of 100 m to 10,000 km is essential. The flow of water of the land surface on scales of 1 m to 10,000 km is driven by differences between the topography and gravity. Topography is required for the correction for aspect and elevation of optical, thermal and radar images on scales of 100 m-10 km. Topography is also of great value in geological studies of tectonic fabric and other surface expressions of lithospheric rifting, and geomorphical studies of many surface processes, for example those associated with weathering, relative sea level changes, and glacial erosion and deposition. A review of the scientific uses of digital land topography has been given by Burke & Dixon (1988).

A wealth of scientific, economic and military purposes may be served by topography in digital form. These uses increase rapidly in number and diversity as its resolution and vertical accuracy improve. Examples of such uses are visualisations of local environments, particularly in conjunction with Geographical Information Systems (GIS). Such systems may be used by planning authorities in the assessment of impacts of construction or land-use change. Digital topography may be important in the routing and siting of radio communication links. The assessment of risks due to flooding, avalanches and landslips requires accurate digital topography. Digital topography is also important as ancillary observations in commercial surveying and scientific field investigations, or for the assessment of logistic transport requirements in surveying remote regions. For many commercial applications, however, it is worth stressing that very high resolution data is required, of the order of metres, and topographic data is often one of a number of data that is required. Other data, such as land use, boundaries and communications are often important.

The measurement of time-variant topography has important scientific and practical uses. On a large scale, vertical motion of the crust is important information in determining the forces acting on it. Steady, secular motion may provide clues as to the rheology of the lithosphere and crust in regions of continental collision or separation, or to the isostatic forces acting on regions of denudation due to weathering. The determination of the inelastic surface displacements provides important information concerning the location and magnitude of stress release in earthquakes (see e.g. Massonnet et al. 1993). Monitoring slow deformation of the surface in regions of earthquake of volcanic activity may provides information concerning the build-up of stress within the crust and the timing of its release. The measurement of time-variant motion may also provide warning of subsidence due to mining, mineral extraction, particularly salt, and water extraction.

2.2. The Status of Understanding and Observations

2.2.1. The Cryosphere

Sea Ice

Sea ice models consist of sub-models of the thermodynamic processes of freezing and melting, and dynamic sub-models of deformation and advection, which are both necessary for realistic simulation of sea ice parameters such as its formation, concentration, thickness and motion. The first thermodynamic models were developed to describe the seasonal evolution of the mean ice thickness in the Arctic under the influence of the surface heat flux, oceanic heat flux, and conductive heat flux. These one-dimensional models divided the ice and snow into several layers and are not presently feasible in large scales studies. To simulate advection of sea ice the dynamic equations of motion for ice and ocean motion must be solved for given forcing fields. The sea ice motion highly influences the ice thickness and open water fraction distribution. In divergence areas leads and polynias are created, which are crucial in the production of new ice as well as for the heat supply from ocean to ice and atmosphere. In convergence areas as well in areas where the ice is piled against the coast, ice deformation and ridging occurs.

The capability of sea ice models to simulate the ice extent under climatological mean and near synoptic atmospheric forcing is documented to be relatively good by comparison with satellite derived ice coverage (Chapman et al., 1994), although significant errors occur in IPCC standard climate models. The predicted sea ice thickness is compared to data obtained from observations sporadic in time and space from submarines (Wadhams, 1994). The models have some success in simulating the climatological ice thickness to within the accuracy of the available data. Their success is practically unknown when the models are forced with near synoptic atmospheric forcing.

A comparison between an observed 16-year mean of Antarctic September sea ice concentration from satellite passive microwaves (SMMR and SSM/I) and the prediction of the present day simulation of the UK Hadley Unified Model is shown in Figure 2.1. The model prediction is larger than the observed extent by up to 50%. The cause of the disparity lies in the parameterisation of the sea ice dynamics, and in the use of flux-corrections at the ocean-ice-atmosphere boundary.

The oceanic heat transport into the ice is partly transported from warmer seas into ice covered areas by the ocean currents. In the last decades, several experiments with ocean models coupled to thermodynamic-dynamic sea ice model have been performed both for the Arctic (e.g. Aukrust and Oberhuber, 1995), around the Antarctic (e.g. Lemke, 1993) and in global ocean modelling. Fully coupled models between atmosphere, ice and ocean are now being developed.

Satellites provide the most important method to obtain repetitive information on the sea ice cover at a range of scales. NOAA AVHRR data are the most extensively used data for sea ice observation. In addition, passive microwave data and high-resolution SAR data are used because they provide ice type information and are not limited by darkness or cloud cover.

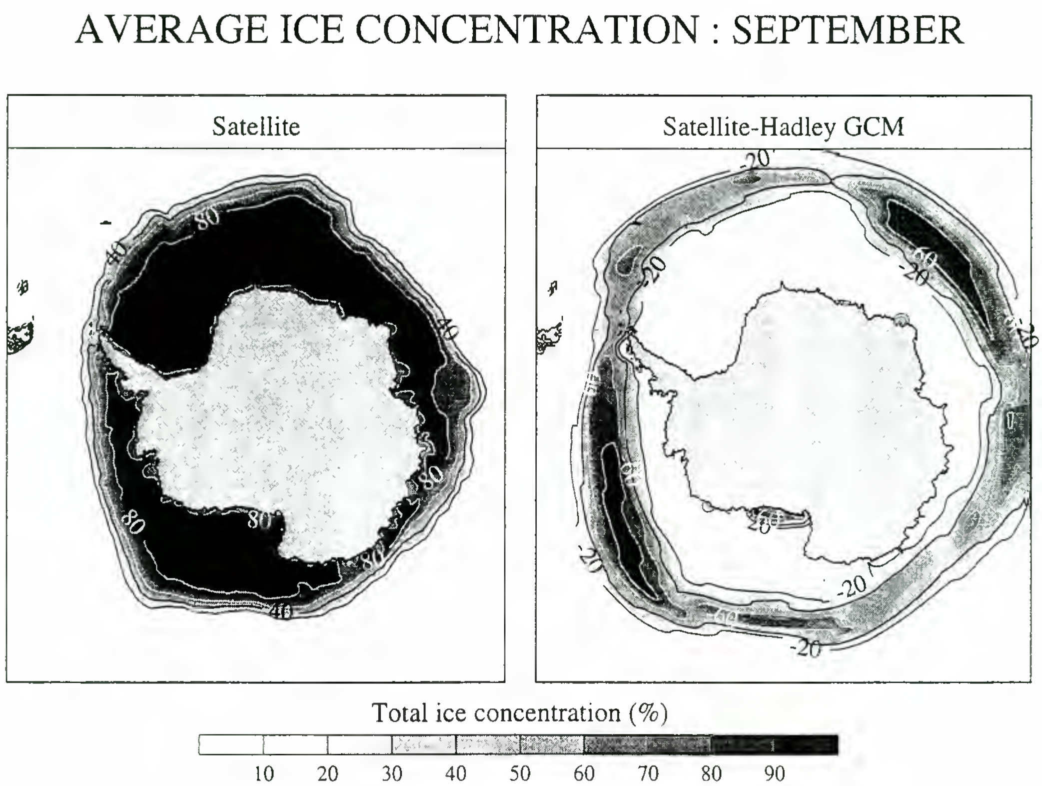


Figure 2.1. *Average sea ice concentration derived from 16 years of passive microwave satellite data (left). Difference of the satellite-derived ice concentration and the Hadley model prediction (right). (Courtesy of Mullard Space Science Laboratory).*

Large-scale sea ice characteristics, such as ice area, extent and concentration of first year and multiyear ice, are retrievable from passive microwave data. The resolution of these data is about 30 km, which is suitable for global and regional ice observations. Several algorithms have been developed to derive the fraction of first-year and multiyear ice. These algorithms have been compared and evaluated (Steffen et al., 1992), and the accuracy of the ice concentration estimates is about 10%. The time series of passive microwave data are very valuable in global and regional studies of seasonal and interannual variability of sea ice extent. Recently, Johannessen et al. (1995) provided a trend analysis of 16 years of SMMR and SSM/I data showing that there is a decrease of 2-5% in the ice area and extent especially in the Arctic. Also scatterometer data from ERS-1 have proven to provide useful data on large scale sea ice properties which can be a useful supplement to passive microwave data (Cavanie, et al., 1994).

Ice classification and mesoscale ice characteristics are derivable using SAR data with a spatial resolution of better than 100 m. From 1991 a large amount of ERS-1 SAR data have been available which has initiated studies of many new aspects of sea ice which were not possible with other data, such as better ice classification, observations of leads, polynyas, ridges, shear zones wave propagation, ice edge eddies and ice freezing. A number of ice classification methods or algorithms for SAR images have been proposed by various research groups.

Ice velocity vectors can be derived from sequential SAR images using algorithms which recognise features and their displacement in the images as illustrated in Figure 2.2. These algorithms are relatively accurate in the interior of the Arctic Ocean, but less useful in the marginal ice zones where identification of ice features is more difficult. The most operational algorithm is the one used by Alaska SAR Facility Geophysical Processing System, mainly in the Beaufort Sea area. With more extensive SAR coverage, as will be afforded by RADARSAT, the ice velocity field in all sea ice areas will be much better quantified.

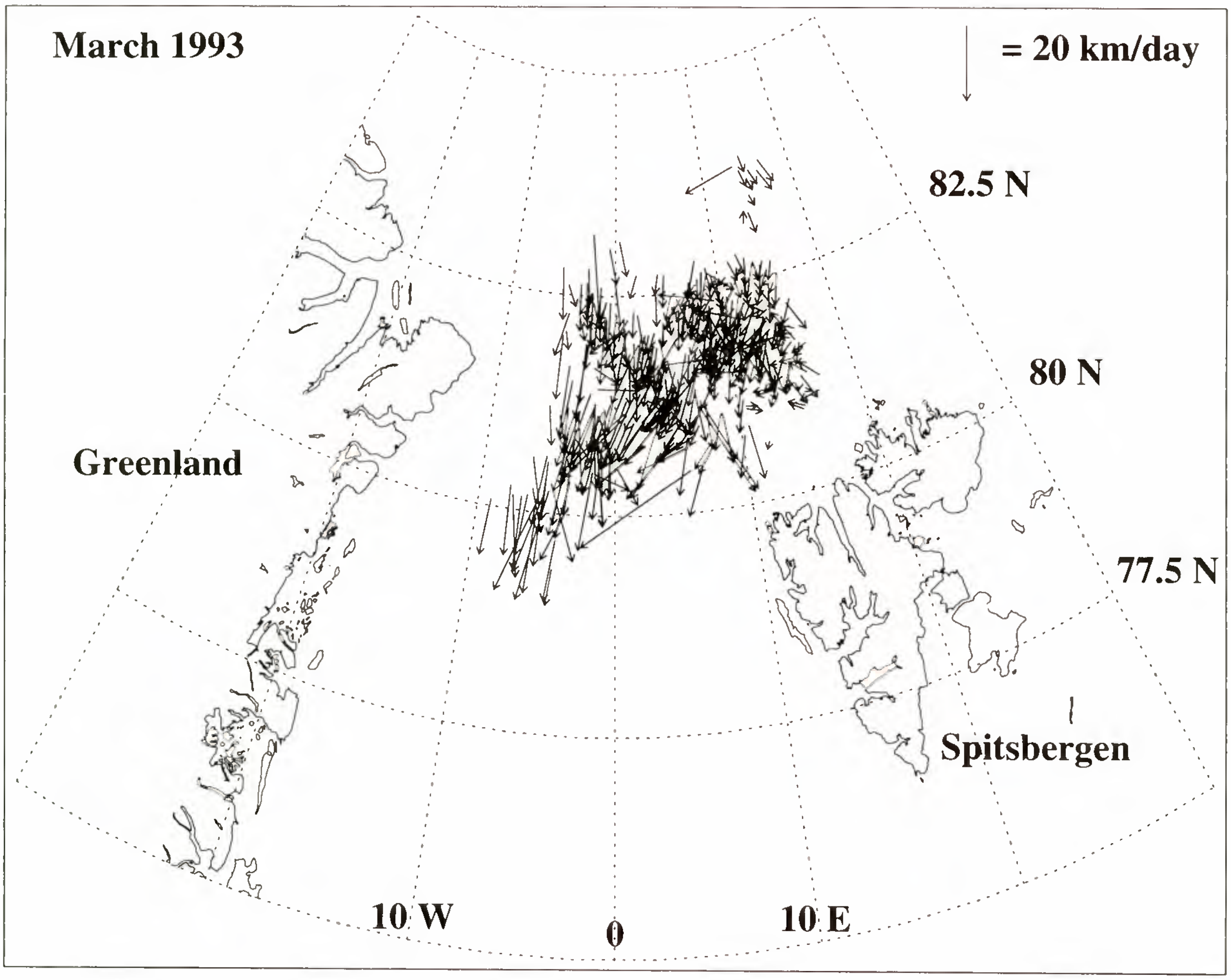


Figure 2.2. Sea ice displacement vectors extracted from sequential ERS-1 SAR images during March 1993. Each vector shown is the average of all vectors from a pair of SAR scenes separated by intervals of up to 8 days (Courtesy of D. Rothrock and A. Schweiger).

Ice thickness is the least known of the important ice parameters needed in ice-ocean modelling. In the Arctic Ocean ice thickness is mainly obtained from in situ measurements taken from icebreakers and ice camps. These data show a mean thickness of 1-3 m in the Eurasian part of the Arctic, increasing to 6-8 m north of Greenland and the Canadian Archipelago. In addition submarine sonar profiles since 1958, which were classified data for many years, have recently been published and show the same general picture (McLaren, 1989). Submarine sonar data is a promising method because the data span large parts of the Arctic Ocean and provide synoptic data sets. It is foreseen that such data will become more readily available as military submarines release data for scientific use. The costs of collecting such data, however, will be very high so it is a question how feasible the method is. The most feasible technique at the moment is upward-looking sonar from bottom-moored buoys monitoring ice thickness at given locations. These data, however, provide time series of thickness measurements only at fixed points. Laser profiling techniques and electromagnetic surveying have been successfully tested from aircraft in the Baltic Sea, but aircraft surveys of the whole Arctic sea ice cover are not practical.

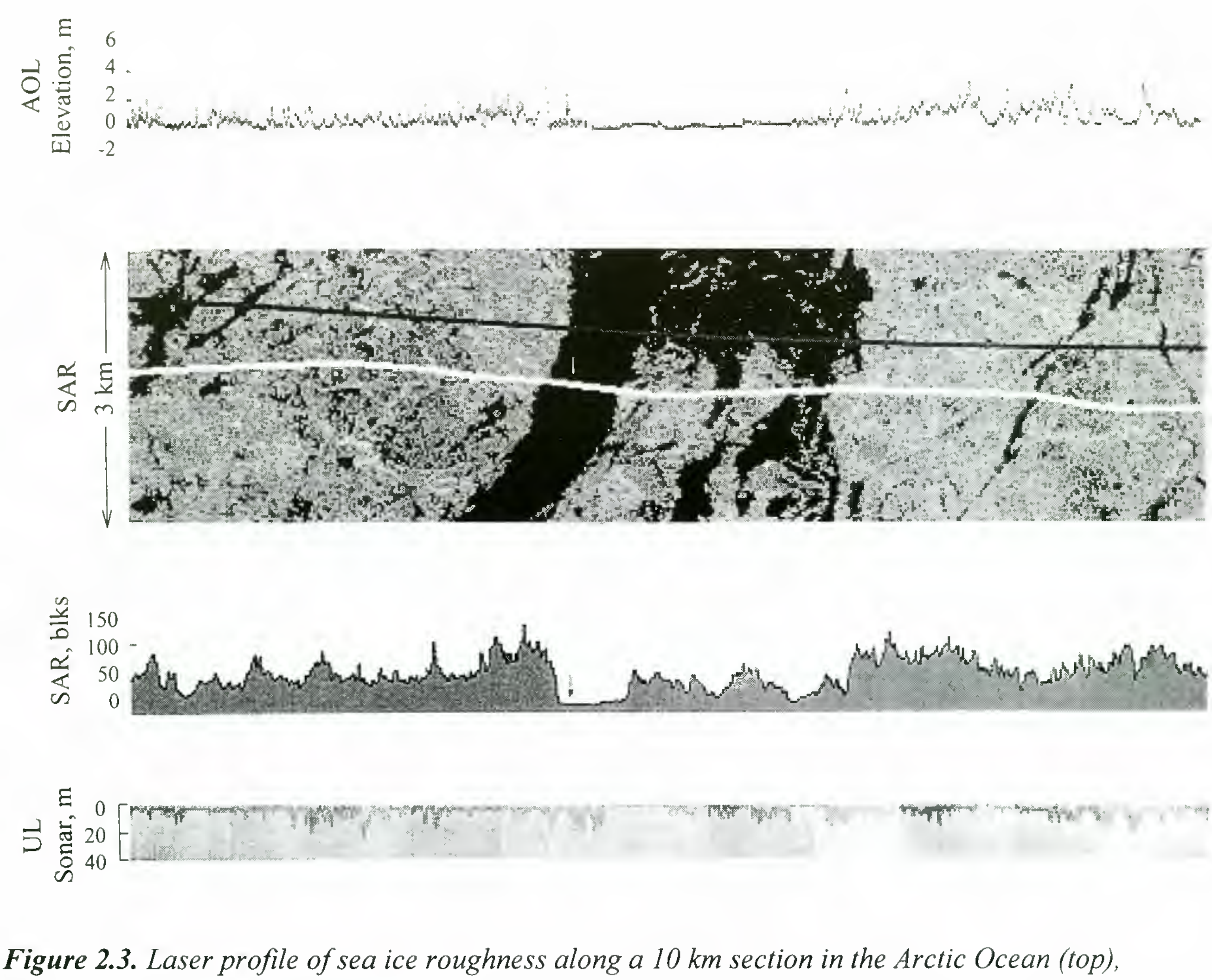


Figure 2.3. *Laser profile of sea ice roughness along a 10 km section in the Arctic Ocean (top), 3 km wide airborne SAR image and corresponding mean intensity variations (centre), and upward looking sonar profile of the ice draft (bottom).*

Airborne laser profiles of test sites in the Arctic sea ice have been obtained during field experiments where also submarine sonar profiles and SAR images have been collected (Comiso et al., 1991). These data show a good correlation between the ice thickness distribution from sonar data and the surface topography distribution from laser data (Figure 2.3). By mapping the surface topography of sea ice it will be possible to estimate the ice thickness distribution. In the Antarctic, very few ice thickness observations exist. However, these limited data indicate an ice thickness distribution different from that in the Arctic. The mean thickness is 0.5-0.7 m, with very few ridges of thickness greater that 10 m. None of the techniques available today are feasible for obtaining sufficient ice thickness data in either hemispheres.

Land Ice

Ice sheets and glaciers exist in dynamic equilibrium between the accumulation of ice from precipitation, and the loss of ice through ablation and through flow to marine shelves and loss through calving. The processes of precipitation and ablation are driven by the atmosphere, and show considerable seasonal and annual variability. The flow of ice and its loss at ocean margins varies on very much longer time scales. The two processes present different observational challenges.

The climatological mean of accumulation and its variance in time over the large ice sheets is reasonably established through ice core data. Its spatial correlation is very much more poorly known, principally due to the sparseness of ice cores. Passive microwave observations are strongly influenced by patterns of accumulation, but such measurements have failed, to-date, to provide reliable quantitative estimates of accumulation. A major source of new information on accumulation is likely to come from atmospheric models, which are now providing estimates of seasonal and spatial variability. This work is demonstrating that the pattern of accumulation is very strongly dependent on changes in atmospheric circulation. Because of the sparseness of ground-based observations, these model estimates provide presently the most important method of independently verifying short term mass balance variations determined by altimetry.

Ice sheets flow as a result of a force balance between hydrostatic pressure gradients generated by their own weight and the resistance to motion resulting from shearing in the lower parts of the sheet or friction to motion at the bed. The understanding that the shape of ice sheets and ice shelves was a result of their near-plastic rheology was fairly recent. Simple models of this kind fit the topography of parts of East Antarctica with considerable success (Paterson 1994). However, much of West Antarctica and Northern Greenland is not well described. Although in general terms this is understood to be related to conditions at the bed, there are very large uncertainties in a proper understanding of the lower boundary conditions (see e.g. MacAyeal 1992). In addition, there are uncertainties in the rheology of ice, which is known to depend on small impurities: The deep Winsconsin ice taken from the Greenland core is markedly softer than the later Holocene ice (Reeh 1985).

Numerical models of the ice sheets (Huybrechts 1994) have reproduced the history of mass decline of the Greenland and Antarctic Ice Sheets, consistent with the view that the large scale variation of the Antarctic Ice Sheet is controlled by sea level (Tushingham & Peltier 1991), and that of the Greenland Ice Sheet by the surface mass balance. The sheet models have very simple representations of bed mechanics, and do not represent ice streams at all, and there are theoretical grounds for suggesting this lack is important. The modelling of ice streams and shelves (MacAyeal 1992) is limited by uncertainties in bed mechanics, in bottom melting and accretion, and in the fracture mechanics at the ice shelf margins. Modelling of the ice shelf interaction with the ocean has also grown in sophistication in recent years (Hellmer and Jacobs 1992).

For large scale investigations of dynamics, the priority is an improvement of ice sheet thickness. Ice sheet bed mechanics are hidden from view, and must be inferred from the behaviour at the surface. The gravitational driving force is proportional to the product of the surface gradient and the ice sheet thickness (Paterson 1994). The knowledge of the surface gradient of ice sheets has been successively improved with the observations of the Seasat, Geosat and ERS-1 altimeters to 82° of latitude (Bamber 1994). These have provided topography over the smoother regions of the sheets accurate to a metre and with a spatial resolution of 10 km. With the exception of the margins, there seems only limited value in improving on this situation because the uncertainties in the ice thickness, the other term required to determine the hydrostatic pressure gradient, are very much larger: In parts of Antarctica, the thickness is not even known.

The situation is very different at the ice sheet margins. The ice sheet/ice stream/ice shelf/ocean interaction remains an area of considerable uncertainty. The drainage of the West Antarctic ice streams is known to be dependent on sub-glacial water, and this can change on short time and space scales. The change in dynamics that occurs at the junction of an ice stream and ice sheet, or an ice stream and ice shelf, where tidal forces come into play, remains a region of uncertain physics. The melting of ice shelves, which is measurable by altimetry if the surface balance can be characterised, is an area of great current interest. Altimetry has been used to map the smoother regions of ice shelves (e.g. Ridley et al. 1989) and attempts (Hertzfeld et al. 1994) have been made to map movement of the grounding lines (the locus of points at which the ice shelve starts to float). However, the steeper gradients and smaller spatial scale of the mechanics limit the value of pulse-limited altimetry. High resolution topographies, at 100 m, is required for dynamical investigations of ice streams, with accuracies of 10 cm.

The mass balance of the large ice sheets may in principle be determined from long time-series of elevation change. The present uncertainty of 400 Gt yr^{-1} in the mass balance of Antarctica is equivalent to a change in ice thickness of 5 cm yr^{-1} water equivalent, averaged over the continent (Jacobs 1992). The corresponding uncertainty for the Greenland Ice Sheet is 80 Gt yr^{-1}. Changes in density and the solid Earth are sufficiently small (Arthern & Wingham

1996) that elevation changes relative to an ellipsoidal frame are sufficiently accurate. The length of the time series is determined at best by natural fluctuations in the ice sheet mass (Van der Veen 1993) and time series of at least 5 years and more usefully a decade are required (Wingham 1995). Observations of elevation change of Greenland have been made from the Seasat and Geosat missions (Zwally 1989). However, these observations have been criticised, particularly for underestimating the magnitude of the orbit error. A number of researchers are presently examining change measurements by combining the ERS-1 altimeter observations with data from other altimetry missions, which provide a 16 year interval for Greenland and a 5 year interval for Antarctica. It is likely that these observations will contribute to improved knowledge of the mass balances of the interior of these ice sheets.

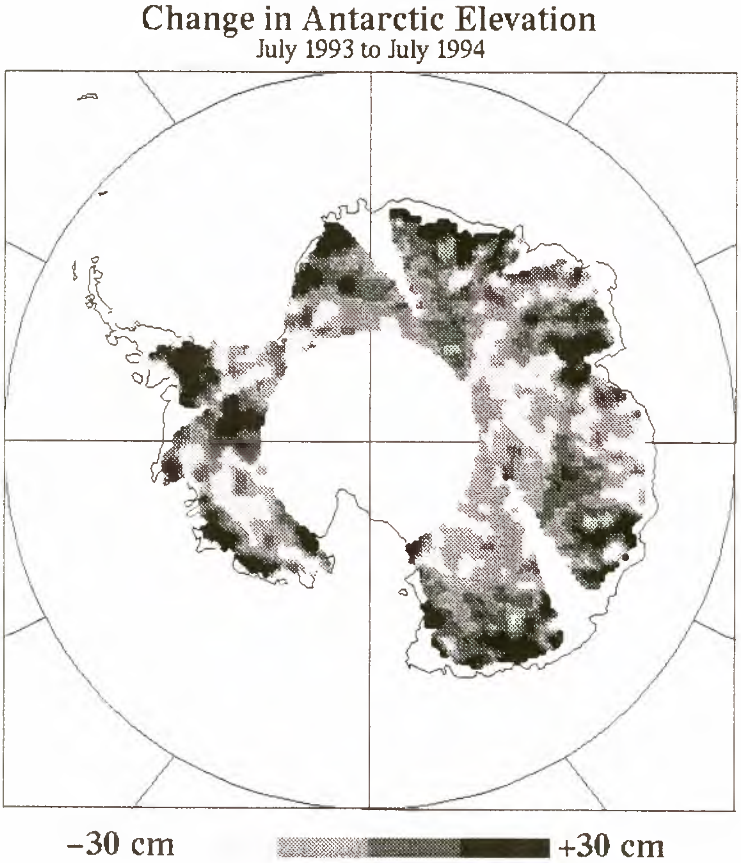


Figure 2.4. The change in ice sheet elevation of Antarctica between July 1993 and July 1994 observed by the ERS-1 radar altimeter. (Courtesy Mullard Space Science Laboratory).

The change in elevation of Antarctica between July 1993 and July 1994 observed by the ERS-1 radar altimeter is shown in Figure 2.4. The figure illustrates the present capability of pulse-limited altimetry to determine ice sheet mass balance. The RMS errors of a 35-day average are of order 20 cm and largely uncorrelated repeat-to-repeat. These errors are too large to permit resolution of the seasonal cycle, although small enough to determine the secular trend over a few years. The margins of the ice sheet, which are responsible for 17% of the mass turn over, are not surveyed by the altimeter because of their high gradients.

Records of small glacier extent have been accumulated by the World Glacier Monitoring Service, some of which extend over hundreds of years. While over the past 140 years, these records support the sensitivity to climate change there is evidence that, since 1960, many temperate glaciers have entered a more 'mixed' regime. However, in many cases there is not a simple relationship between glacier extent and glacier mass. Exposure to local variations in climate, and variations in flow dynamics, make prediction of the future evolution of these ice masses uncertain.

2.2.2. The Oceans

Ocean models must be able at the very least to provide the sea-surface temperature and moisture fluxes and their temporal evolution, a major coupling of the atmosphere/ocean system. A good candidate would have primitive-equation dynamics and thermodynamics, and a vertical and horizontal resolution high enough to adequately model the surface layer and the mesoscale eddies contained in the altimetry data record. As in the atmosphere, representing the eddies and low-frequency waves (as in Jacobs et al., 1994) in ocean models is generally thought to be necessary for climate studies despite the cost involved. The alternative of parameterising the eddy-mean interactions as well as the meridional eddy heat fluxes rather than explicitly representing them has shown to significantly degrade the results (e.g. Beckmann et al., 1994).

Global ocean circulation models with adequate resolution and efficient data assimilation methods are now reaching maturity both in North America (Los Alamos, NCAR; e.g. Semtner, 1995) and in Europe (ENVIRONMENT programme). WOCE activities through the WOCE Community Modelling Effort (CME) (e.g. Böning et al., 1995) have made particular progress in North Atlantic circulation modelling. Remaining problems include the specification of isopycnal and diapycnal mixing (Gent and McWilliams, 1990), the quest for a suitable parameterisation of mesoscale processes and deep convection in low-resolution models, and the poor specification of model errors in data assimilation schemes.

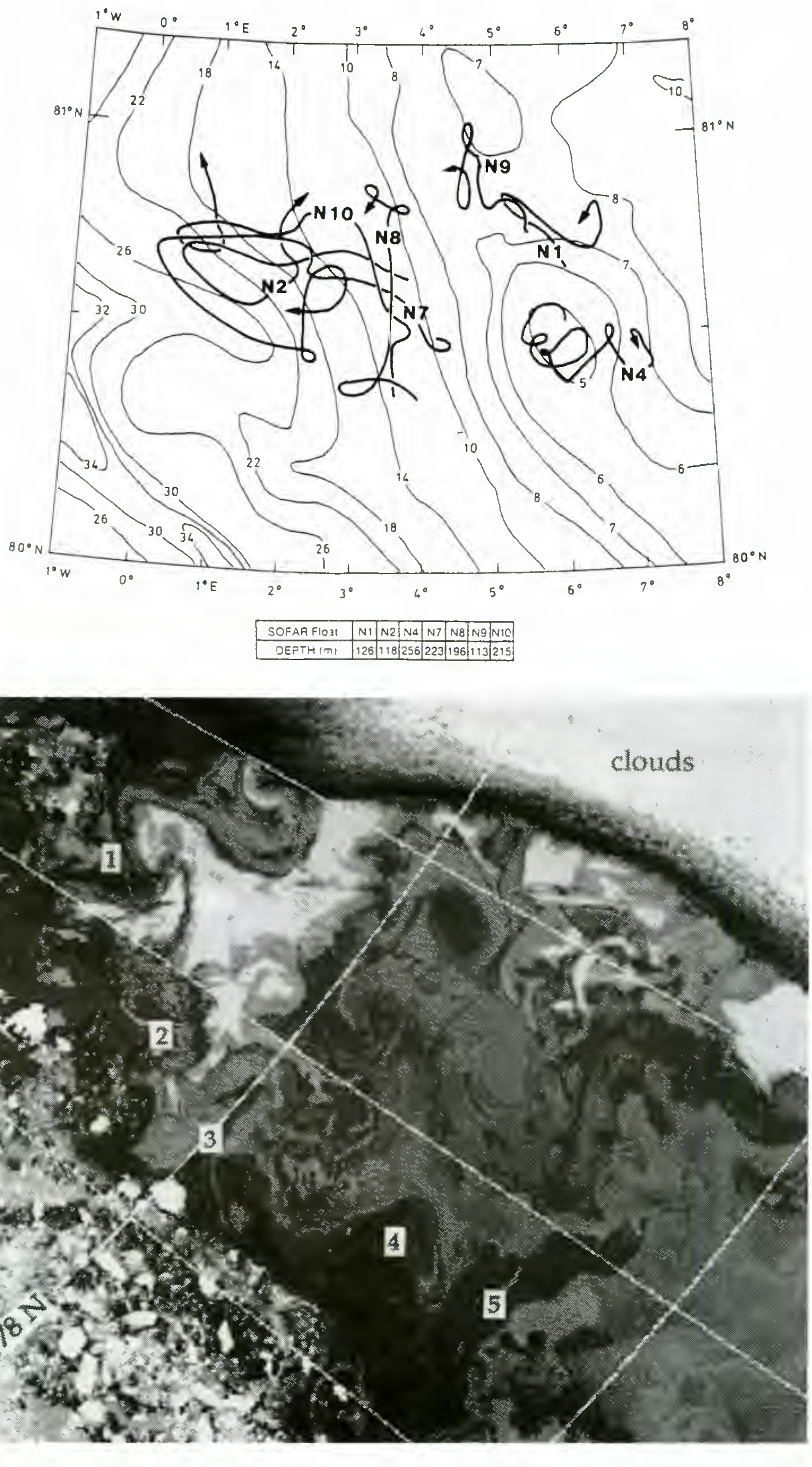
As far as data assimilation is concerned, a full spectrum of methods tested both in the atmosphere and the ocean is now available (e.g. De Mey, 1996). However, the problem is at least two orders of magnitude larger than its atmospheric counterpart because of the smaller oceanic scales. Methods to reduce the order of the problem while keeping some optimality are appearing, such as the highly-parallelizable representer method. Another difficulty is that model error statistics are unknown, which is different for the atmosphere. The errors are needed in order to perform reliable predictions. In order to access them, models must be run for long times (10 years or more) with a continuous data flow. The problem of transferring vertically the surface topography to the whole water column is not fully solved. Promising methods involve the use of isopycnal empirical orthogonal functions (Gavart and De Mey, 1996). One advantage of assimilation is that it provides a general framework in which the information contents of the measurements can be expressed. The high-precision altimeter systems measure some processes such as high-frequency atmospheric pressure forcing or sea-level drifts which are not represented in models. It is therefore essential that studies on the physics of the topography measurement be pursued, because processes which were formerly neglected become significant, and because measurements become more accurate.

Coupled modelling can serve a central role and act as a unifying function among the various climate subsystems among which are the ocean, atmosphere, sea-ice, and coastal areas. Areas of desirable implementation at the periphery of ocean models include coupled atmosphere/ocean modelling, a very active field (e.g. Meehl, 1990a,b for coupled El Niño modelling), ocean/cryosphere/atmosphere modelling (see below), ecological/ physical modelling, and embedding of coastal models in larger-scale models. In particular, coastal and ocean shelf models will use local data sources and will require the coupling between physical processes such as tidal currents, storm surges, open-ocean dynamics, and river runoff. Therefore the dual-scale/dual-physics approach with embedding is the most reasonable approach. In addition, a single altimetric mission cannot be expected to provide by itself an adequate coverage in any portion of the world coasts. Finally, altimetry in coastal areas will require specific tidal and sea-state corrections.

Ocean circulation at high latitudes and its interaction with sea ice and the atmosphere is only now being properly addressed in climate change studies. In particular, sea ice controls the heat and moisture fluxes between the ocean and atmosphere. The age of ice is an important factor because it influences how much fresh water is released in the ocean. Ice transport southward from the Arctic provides an important source of fresh water to the Greenland and Norwegian seas impacting the deep convective overturning and bottom water formation in this region. This process may influence the global-scale thermohaline circulation. On the other hand, the ocean eddies and currents influence the ice drift on various scales (Figures 2.5). Efforts are ongoing in the ocean/sea ice/atmosphere coupled modelling as well (CLIVAR Science Plan). Particular applications for the ocean include the parameterisation in the ocean model of ice formation and rafting and heat loss through leads in the sea-ice.

Satellite sensors such as altimeters, scatterometers and (to a lesser degree) radiometers are the only observing systems providing direct, continuous, and quantitative measurements of the ocean surface on global scales over the long periods suitable for data assimilation and climate studies. The altimeter measures the variable topography, a signature of surface geostrophic currents, and the mean sea level, a quantity showing volumetric changes (e.g. Larnicol et al., 1995). Global models assimilate the former. Satellite missions and measurements must be appropriately phased with respect to each other. Desirable combinations include the following:

- A gravity field mission which would allow the altimeter data to be processed in such a way as to determine the absolute ocean surface circulation, which is an essential component of climate models.



SOFAR Float	N1	N2	N4	N7	N8	N9	N10
DEPTH (m)	126	118	256	223	196	113	215

***Figure 2.5**. Drift trajectories of sofar floats deployed at depths from 100 to 250 m (thin lines indicate water depth in hundreds of metres) (top). NOAA AVHRR image from 1 July 1984 showing mesoscale meandering ice edge-ocean features such as the eddies and ice tongues (numbered 1 to 5) (bottom). (Courtesy: Johannessen et al., 1987).*

- Simultaneous wind (scatterometer), sea-surface temperature (radiometer) and topography (altimeter) measurements could be assimilated in a coherent manner in coupled ocean and atmosphere models.

It is not possible to optimise the sampling of any single satellite mission to observe all oceanic processes and regions. The sampling problem must be thought in terms of complementarity. The overlapping of ERS-1/2 on a 35-day orbit and the 10-day orbit of TOPEX/POSEIDON in 1993 and in 1995 onwards illustrates such a complementarity: the fast-varying tropics, large-scale disturbances and western boundary currents require the latter, while the mesoscale and high latitudes are adequately observed by the former.

In the absence of a sufficiently accurate geoid, altimetry measurements will refer to an unknown mean. This translates in data assimilation context into the fact that the model mean (usually derived from atlas data such as from Levitus, 1982) cannot be objectively improved by altimetry. Recent studies (e.g. De Mey, 1994) have shown that the model mean can be changed by the assimilation of fluctuations via eddy-mean flow interactions such as Reynolds stresses, but it may not converge to the truth. The mean barotropic component in particular is almost free of any data constraint in most parts of the world ocean, although inverse models can be used (with mixed results) in order to access it. Another problem is the lack of salinity information, especially in the southern hemisphere and at depth. As far as climate studies are concerned, the mean circulation is responsible for a significant part of the large-scale advection of tracers (including temperature, salt and CO_2), and it influences the turbulent transfer of heat in the meridional direction (Bryan, 1991).

2.2.3. The Land

The economic and military value of topography, together with communications and land-use, is such that all countries of the world have mapping institutions, typically with responsibilities extending to national borders. There are few parts of the world, with the exception of Antarctica, Greenland and some remote regions of Canada, for which topographic elevations are not available in map form at scales of 1:1000000 or better and with a contour interval of 500 m or better.

The status of global digital elevation data, however, is quite different. Until very recently, the only global model of Earth's topography was ETOP05, or its derivatives. This model has a nominal resolution of 10 km. Comparisons of this model with radar altimetry returns from the land surface measured by Seasat, showed the model to have RMS errors of order 100 m, which is equal to the variance of the land topography at scales of 100 km. This model was assembled principally for the representation of the land topography in large scale climate models. Other models have since appeared, based on digital forms of US Navy 1:1000000 charts, which have considerably improved spatial resolution, but remain poor in the vertical. The models are a considerable improvement in mountainous regions, but provide very poor representations of gradients in regions of low relief. All these models are digitisations of contour maps of orthometric heights. They contain error resulting of uncertainties in the geoid, which can amount to tens of metres in parts of the world, and through faults in digital assembly. They also take little account of the definition of local ellipsoids.

The ETOPO5 model of relief of the Earth's surface, which samples the Earth at 5 arcmin, or around 10 km is shown in Figure 2.6. The data were compiled from various sources.

These models satisfy some, but not all, large scale scientific applications. From a comparison with radar altimeter data, Wingham & Devayya concluded that the models were accurate representations of scales down to 100 km (degree 180). At smaller scales, the errors exceeded the topographic variability. The implications of this are:

- For the global comparison of topography and gravity, this resolution greatly exceeds the resolution of current gravity models. In addition, errors in ocean bathymetry greatly exceed those of land topography. On continental scales the data is more accurate than the corresponding gravity in many parts of the world. Conversely, the data is more or less useless for the correction of local gravity surveys. These data are also of too poor a resolution for the study of weathering models and rates.

- For global climate modelling, the data are sufficiently accurate. For regional climate modelling (10^2 km scale) the data are too poor in many parts of the world.

- For hydrological modelling the data are too poor even at continental scales. However, the realistic modelling of hydrology is in its infancy, and requires many other related data. Hydrologic modelling requires very accurate gradient information.

- The data are too poor for image correction.

- The data are too poor for geological and geomorphological investigations.

- The data of little commercial value or practical use.

An improvement of low-resolution models is now possible using the geodetic phase of the ERS-1 radar altimeter provided more-or-less continuous coverage of the land surface below 800 m at 10 km resolution. Although in mountainous regions the elevations are contaminated by off-ranging effects that limit their vertical accuracy to 50 m and make them of limited value, these data can be expected to greatly improve the representations of gradients in low lying areas such as the Amazon basin.

Figure 2.6. *The Earth and Ocean Topography with 5 arcmin (about 10 km) raster resolution displayed as shaded relief. (Source NOAA-NGDC, courtesy of DLR).*

High resolution digital topographies are available for certain parts of the world. In a world-wide survey of 350 mapping institutions Wolf & Wingham (1992) identified all the high resolution maps (less than 250 m) in the public domain. This amounted, essentially, to complete coverage of Europe, US and Japan, and virtually none outside it. Better models do exist, of which the best known is the US Defence Mapping Agency (DMA) DTED (Digital Terrain Elevation Data), that is known to have virtually complete coverage at 100 m resolution of the Northern Hemisphere, and some of the Southern Hemisphere.

Stereo-photogrammetry, particularly the French SPOT series of satellites, has provided 5 m resolution topography of customer-requested areas of the Earth for the past decade. With some local exceptions, digital topographic has significant economic value only at very high resolutions of 10 m, or in some cases significantly better, and often needs to be combined with other data showing land-use, boundaries and communications. The ERS-1/ERS-2 Tandem Mission is now providing extensive interferometric coverage of the Earth which will also contribute to improving the availability of DEMs.

High resolution data covering much of the land surface is in existence, but presently remains classified. The most important such model is the NATO DTED model, which covers extensive parts of the land surface at 1" × 1" and 1/3" × 1/3" resolutions with accuracies between 1 and 5 m.

The coverage of the Defense Mapping Agency (DMA) 3 arcsec (around 100 m) resolution elevation model of the Earth's land surface is shown in Figure 2.7. These data are deresolved to 1 km and included in the GLOBE data set.

Figure 2.7. *Availability of the DMA 3 arcsec (100 m) resolution elevation data. These data were downsampled to 1 km raster resolution and included in the Global Land One Kilometre Base Elevation (Courtesy of DLR)*

Recognising these problems, an Auxiliary Data Subgroup of CEOS-WGD was formed in 1992 to conduct the Global Land One-kilometre Base Elevation (GLOBE) project. It is a 1 km, gridded, quality-controlled digital DEM. The elevation contours are from the 1:1.000.000 Operational Navigation Charts, placed into the Digital Chart of the World (DCW with 1 km gridding at nominal latitude-longitude spacing). The currently available higher resolution (than GLOBE) DEMs are sampled and inserted into GLOBE. The DEMs are derived from stereo-optical and radar satellite imagery and from altimetry. For regions where these sources data are not available, resampled data from DEMs of lower resolution are inserted. The final product release is planned for 1996 in two forms, namely as 'BAD GLOBE' (Best Available Data) to a restricted community, and as 'GOOD GLOBE' (Globally Only Open-access Data) in an unrestricted form.

2.3. Existing Plans for New Observations

2.3.1. The Cryosphere

Sea Ice

There are a number of observations and scientific plans for the Arctic Ocean and the Southern Ocean where sea ice research and monitoring are key elements. Within the framework of the World Climate Research Programme there are several programmes which focus on sea ice research: ACSYS – Arctic Climate System Study, AITMP and AnITMP – Arctic and Antarctic Sea Ice Thickness Monitoring Programmes, and IAPB – International Programme for Antarctic Buoys. These programmes include use of satellite data, but focus also on collection of ice parameters which cannot be obtained from satellites at the moment, such as ice thickness.

Large-scale ice extent, area and concentration have been observed by passive microwave imaging radiometers for about two decades. This will continue in the future with the Special Sensor Microwave Imager (SSM/I) on DMSP and the Advanced Microwave Scanning Radiometer (AMSR) on ADEOS II from 1999. A useful supplement to the passive microwave instrument, in mapping of ice parameters on large scale, will be the scatterometer which has been demonstrated by ERS-1. In addition to the ERS scatterometers the NASA Scatterometer (NSCAT) is planned for ADEOS (1997), and SeaWinds on ADEOS II (1999). Useful data for sea ice observations will also be available from moderate resolution visible to thermal infrared radiometers and spectrometers such as the Advanced Very High Resolution Radiometer (AVHRR) on NOAA-series and METOP-series and the Advanced Along Track Scanning Radiometer (AATSR) on ENVISAT.

Ice motion, ice type classification and mesoscale ice characteristics such as leads, polynyas, ridges, floe size distribution will be mainly obtained from synthetic aperture radars, which have been successfully demonstrated by ERS-1 since 1991. ERS-2 will replace ERS-1 from 1996 onwards and secure SAR data until the end of 1999 when ENVISAT ASAR will become fully operational providing various modes of SAR data including wide swath (405 km) mode and alternating polarisation (100 km) mode. RADARSAT, moreover, will provide various modes of SAR data from 1996, the most important for ice monitoring will be the 500 km wide ScanSAR mode. With the large amount of SAR data available in the next decade it is expected that the knowledge about sea ice and its dynamic and thermodynamic interaction with the atmosphere and the ocean will be considerably improved.

For small-scale sea ice processes, the SAR will play a central role, but there will be important supplements from fine-resolution visible to infrared imagers such as the Enhanced Thematic Mapper (ETM) on Landsat 7 from 1999, the High Resolution Visible and Infrared sensor (HRVIR) on SPOT 4 from 1997, the Advanced Visible and Near-Infrared Radiometer (AVNIR) on ADEOS 1 & 2 from 1997, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on EOS AM 1.

For ice topography laser altimeter profile data from EOS Laser ALT (ICESAT) will be available from 2003.

Land Ice

There are a number of important planned or recently-launched missions with mapping and topographic capability which will greatly increase our knowledge of ice sheet and glacier extent, and of ice sheet and glacier topography.

The ERS satellites (1991 and 1995) has provided and will continue to provide a wealth of interferometric coverage of the Antarctic and Greenland Ice Sheets, and of smaller glaciers and ice caps. Improvement in the topography, extent and velocity structure has already been demonstrated in Antarctica, Greenland, Patagonia and Svalbard. In particular, the ERS tandem mission with the one day separation has provided interferometric data with very good coherence. The Radarsat mission (1995) will provide the first complete SAR coverage of Antarctica. SAR interferometry of ice sheets is complicated by the motion of the ice, and improvements in the stock of ground control data, of both elevations and velocities, may be necessary over the ice sheets if the full value of these data are to be realised. Other important ice mapping missions include the ASTER instrument flying on the EOS AM platform satellite which will provide optical mapping at 15 m resolution with a potential for stereo mapping. The ENVISAT ASAR (1999) will also provide interferometric mapping of Antarctica to 80°, and of all of Greenland.

Ice sheet mass-balance will be greatly improved with the time-series provided by the ERS and ENVISAT satellite series. It will extend the time series of Greenland and Antarctic observations to 1998 and into the decade. NASA intend to revisit with geodetically tied airborne lasers a network of survey lines in Greenland. These observations will provide important independent observations for comparison with the satellite altimetry. The EOS Laser ALT programme, due for launch in 2003, will provide laser altimeter coverage to 86° of latitude. These data may provide the first systematic repeated surveys of the Ice Sheet margins. However, it is not known to what extent cloud will effect its results. Cloud climatologies are poor in Antarctica and Greenland, because of the difficulty of differentiating the cloud and ice sheet temperature in satellite imagery.

There are also a number of important ground and aircraft-based programmes; GLOCHANT, is being proposed under the auspices of SCAR, whose aim is to reduce the uncertainty in the balance of Antarctica to 200 Gt yr^{-1}, by aircraft survey of discharge velocity at the margins. A multinational traverse of East Antarctica, ITASE, is planned to start in 1996/7. Among its goals are regular shallow cores across the East Antarctic. Nationally funded field-programmes of the Greenland and Antarctic ice sheets will continue, particularly of the dynamics of the ice sheet/stream/shelf systems (SCAR 1994). The Ross Ice Shelf programme, (RISP) and Filchner Ronne Ice Shelf programme (FRISP) are examples.

2.3.2. The Oceans

There are a number of plans for ocean observation programmes. The CLIVAR climate science sub-programmes will include ocean observations. Coastal measurements of various kinds are likely to occur in the frame of the operational activities of GOOS. However the majority of large-scale observational programmes are spaceborne. Planned altimetry missions include ENVISAT/RA-2, the GEOSAT Follow-On (GFO) series, and the high-accuracy TOPEX/POSEIDON (T/P) Follow-On (TPFO) series (see below). There will be a number of opportunities for measuring ocean colour and sea-surface temperature into the next decade, including the MERIS and AATSR instruments on ENVISAT and other European, American and Japanese missions. Scatterometer sea-surface winds will be measured by NSCAT and Seawinds on the ADEOS series as well as from ERS-2, and possibly by METOP (ASCAT) during the next decade.

The TPFO series could, if decided, start with a first launch in 2000. The sampling and other satellite characteristics would be almost identical to those of T/P. It has been shown that such a set-up provides an adequate coverage of the tropical areas and general circulation variability; in addition its excellent error budget has given access to precise measurements of sea level, including seasonal steric height changes and interannual sea-level drift. T/P also revealed a large interannual variability both in the tropics and in the subtropics, which also justifies a requirement for 'long' time series. However the TPFO orbit will not cover the high latitudes beyond 66°, and its 10-day-repeat ground track network will be too wide-spaced to resolve the mid-latitude mesoscale eddies.

The GEOSAT Follow-On (GFO) series of the US. Navy will start with the launch of GFO-1 in late 1996 or early 1997. The initial mission is planned for five years. The continuation of the series beyond 2002 is not decided yet. As it is now considered, the GFO series will have the same 17-day repeat orbit and ground tracks as GEOSAT, which has a maximum latitude of 71.2°, and a payload with minimal specifications (single-frequency RA, no radiometer). The classification status of the measurements have yet to be decided.

The Earth Explorer Gravity Field and Ocean Circulation Mission (ESA, 1996), proposed as one of the nine ESA Earth Explorer missions, is intended to accurately determine the geoid down to 50 km resolution with an accuracy of 2 cm. This mission would allow the reprocessing of the measurements of past satellites with sufficient accuracy in order to provide the absolute signal and an estimation of the mean to better constrain the models. The CHAMP mission (1999) will map the gravity field to degree and order 30 by the end of its mission lifetime.

2.3.3 The Land

The practical importance of digital topography has led to a significant number of public sector and commercial ventures aimed at providing digital topography. Improvements may come through four mechanisms: the release of previously classified terrain models, customer-driven satellite acquisition of stereo-images, dedicated use of the ERS satellites, in particular the tandem interferometric data, and a dedicated land topography mission.

The declassification of existing data is the most rapid way of improving public knowledge of the Earth's land topography. The NATO DTED data is the best representation of the Earth's land topography in existence. Two possibilities are presently being explored. One is the release of DTED-2 1" × 1" model with 3-7 meter accuracy, the other is the release of the DTED 1/3" × 1/3" data with 2 m accuracy. At the time of writing, it seems likely the first of these may be achieved.

Stereo-photogrammetry with the EOS AM platform (1998/89) will provide stereo mapping similar to SPOT. Stereo-photogrammetry with single-pass optical mapping will be available from SPOT-5 (2002) and the German-Russian MOMS-2P (1996), both with a resolution of 5 m. A Japanese satellite ALOS is planned for 2002 with an resolution of about 3 m. In addition, three US commercial systems with mapping capabilities are planned between 1996 and 1998. However, much of these data will not be publicly available.

Dual pass SAR interferometry with the ERS satellites presently provide interferometric radar coverage of much the Earth's land surface. The ERS-1/ERS-2 Tandem mission provides presently interferometric data for DEM generation over a large part of the Earth's land surface. These data will probably remain the most important existing source of timely improved topography over large areas in the near future.

Single pass SAR interferometry is planned with the SLR-3 shuttle flight around 2000. In an 11-day mission, global interferograms between the latitudes 59° N and 57° S will be obtained at C-band (full coverage) and X-band (part coverage) (Figure 2.8). A boom of 60 m across track will be applied and the mission is called Shuttle Radar Topography Mapper (SRTM). It should provide in a 1" × 1" grid a DEM with a vertical accuracy of 3 m to 7 m, or even a 2 m to 5 m accuracy in a 1/3" × 1/3" grid. This is the most important land topography mission in the next decade.

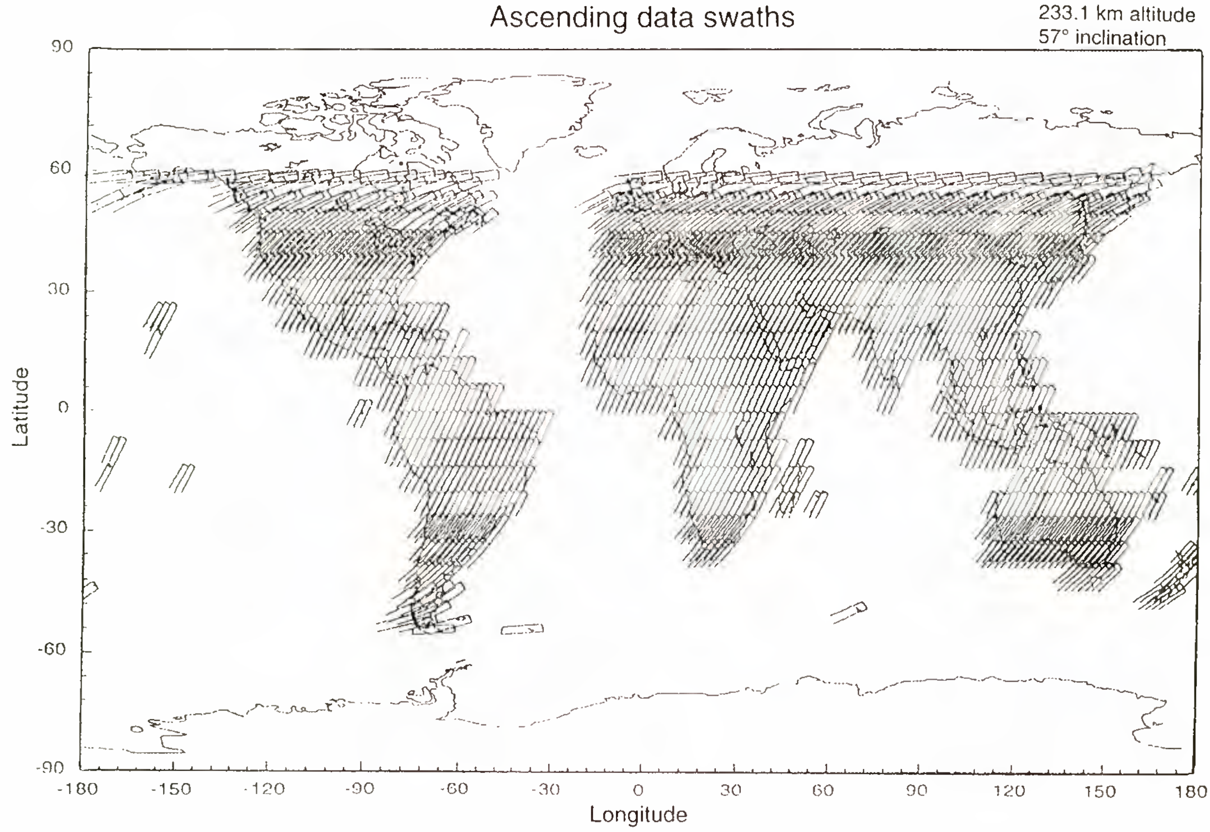


Figure 2.8. Coverage of descending tracks obtained from the planned Shuttle mission

2.4. The Role of the Earth Explorer Topography Mission

From the above it is evident that significant gaps remain in our understanding and knowledge of the high latitude ocean and cryosphere and in existing plans for observations, which are mainly concerned with the tropical and mid-latitude climate. Principal among the gaps is the present inability to systematically investigate the mass flux and surface roughness of sea ice, which has many consequences. It limits the ability to estimate the momentum exchange between the atmosphere and ocean, which also effects the wind speeds and thence the local surface heat budget. It also limits the ability to estimate the poleward heat flux, and the exchanges and transport of freshwater in the polar oceans. Verifiable improvement of the characterisation in coupled climate models of the sea ice mass flux and its consequences is difficult, because there are too few observations of parameters such as thickness. In addition, it has not been possible hitherto to study simultaneously and over large scales the coupling between sea ice and ocean currents, which are both influenced by the ice and determine its long term transport.

Changes in the mass of water sequestered from the oceans and the atmosphere, over periods of a decade, will depend on the accumulation, surface transport and dynamics of the margins of the large ice sheets and the small ice caps and glaciers of the world. This mass exchange is small in comparison with those between the land, oceans and atmosphere in the tropics, but the hysteresis in the mass exchange with the cryosphere is the principal cause of interannual and longer changes in ocean mass. However, at present, there are no observations that routinely monitor this mass exchange. Pulse-limited altimetry seems likely to provide the secular drift of the central parts of the large ice sheets over 5 years or so of observations. However, as much as 17% of the most dynamic components, the ice sheet margins and smaller ice caps and glaciers, and all of those components likely to effect sea level over the next century, are presently unmonitored.

The Earth Explorer Topography Mission provides, uniquely, an opportunity to greatly increase our understanding of these phenomena, and to initiate their systematic monitoring. These problems have not been accessed by present instrument systems because they require an instrument that combines high spatial resolution and absolute vertical accuracy. Such instrumentation is now feasible and has been demonstrated on aircraft. The mission is therefore scientifically and technologically timely. The mission will also provide other important benefits. If flown in parallel with an altimetry mission of the TOPEX/POSEIDON class, the mission can make a major contribution to global climate prediction models of ocean 'weather'. The mission can also make an important supporting contribution to land applications, by providing spot heights that may be used to control interferometric products from current or near-future missions. It will also permit for the first time the remote gauging of rivers, which may prove in time to have very important applications in water resource management.

2.4.1. Scientific Goals of the Mission

To address the above mentioned gaps in our understanding and knowledge the scientific goals of the Earth Explorer Topography Mission are to properly measure:

Seasonal and interannual fluctuations in sea ice thickness. It is well known that the characteristic thickness of first-year ice is 0.5-2 m and multi-year ice is 2-4 m. But a more accurate knowledge of regional variability, the climatological mean, seasonal and interannual fluctuations in the thickness is lacking, which has very important implications for the numerical modelling of climate and climate change:

- The mass flux of Arctic and Antarctic sea ice is poorly known. The total ice mass can only be estimated with an accuracy which is not better than ± 50%, due to the lack of ice thickness data, especially in the Antarctic.

- Sea ice is a large reservoir of freshwater which is advected with the ice drift and has large seasonal variability. The exchange of saline and fresh water as the ice grows and decays is an important mechanism influencing global oceanic thermohaline circulation.

- The thickness distribution determines the heat exchange between ocean and atmosphere. Since ice thickness distribution data are scarce the heat exchange estimates are poor, as well as the ice production due to conductive heat exchange in ice covered areas. The quality of the ice thickness estimates as well as conducted heat flux generated by sea ice models is therefore difficult to assess.

- The roughness of the ice strongly effects the momentum transfer from the atmosphere to the ocean. The ice thickness distribution therefore provides essential information as to the behaviour of the atmospheric boundary layer and the rheology of the ice.

- Long-term trends in ice thickness can be interpreted as a response of sea ice to climate change (Wadhams, 1994).

Seasonal and interannual fluctuations in the mass budget of ice sheets and glaciers. The mass balances of the margins of the large ice sheets and many of the smaller ice caps and glaciers is unknown. Together these balances are the most important uncertainty in determining the present rise in eustatic sea level:

- The margins of the Antarctic and Greenland Ice Sheets are the regions of largest mass turn. They are also the regions of ice sheets most exposed to atmosphere- and ocean-driven changes. They are therefore the most dynamic parts of the ice sheet component of the global water budget. In the event of global warming, it is the margins of the ice sheets that will provide any ice sheet contribution to the resulting acceleration in eustatic sea level.

- Small ice bodies and glaciers are the most dynamic ice reservoir of water. The determination of the contribution of small ice caps and glaciers to eustatic sea level is based on correlation between glacier extent and temperature over the past century. Direct observations of mass variations is required for properly monitoring these ice bodies.

High latitude ocean circulation and global climate prediction. The spectrum of variability of the world's oceans cannot be accessed with a single altimetric satellite. The Earth Explorer Topography Mission has a central role to play in describing and mapping the high latitude currents in conjunction with simultaneous sea ice measurements. A major challenge is the small scales associated with mesoscale currents and eddies (the Rossby radii are less than 10 km).

- The high latitude circulation has important large scale affects on the climate. On longer time scales it determines the advection of sea ice, which is an important source of freshwater advection, particularly in the Greenland and Norwegian sea. This affects deep convective overturning and may impact the global thermohaline circulation.

- In addition, if the Earth Explorer Topography Mission is flown in conjunction with a system of the T/P class, it can make a major contribution to global climate prediction studies. The ocean mesoscale at all latitudes (the ocean 'weather') is an essential component of ocean circulation because of its limited predictability, non-linear interactions with the mean flow and role in water mass dispersal. These interactions are even more complex in coastal areas, where the mesoscale, tides, storm surges and mean currents are coupled. Both the physics of the interaction, and the techniques for the numerical embedding of these phenomena will become an important area of research in the next decade.

2.4.2 Other Benefits of the Mission

Sea ice extent, concentration and ice type. High resolution altimetry of sea ice has the potential to determine more than simply thickness and roughness of the ice. The ice extent, concentration expressed as a percentage of open water, and the ice age, may all be determined from high resolution altimetric observations. Ice age is an important quantity for oceanography, because it controls the amount of freshwater released to the ocean. While these measurements are not unique, and will not compare in temporal sampling with wide swath microwave observations, they may provide an important alternative source of data, particularly in regions of low concentration, where in particular passive microwave determinations are uncertain.

Lakes and inland waters. Altimetry may also be used to determine the height and variation in inland water bodies. Although still immature as an application, time series of lake levels and wetlands levels may prove in time to have a very important role in water resource planning and management, particularly in regions of the world where ground-based planning and management is extremely limited. To date, such applications have been restricted to large lakes and inland waters because of the limited resolution of pulse-limited systems. The Earth Explorer Topography Mission would considerably increase the number of water bodies available for monitoring. In addition, the satellite gauging of rivers, which has been very largely impossible with pulse-limited systems, would become a very interesting possibility with high spatial resolution altimetry, albeit that some of the time scales of variation can be shorter than those accessed by the altimetry.

Spot heights for interferometry. The next few years will see a very large body of dual and single satellite interferometry data of the Earth. A very important application of these data will be the production of digital elevation models of the Earth's topography. However, the observations provided by interferometry are ambiguous as a result of the phase of the signal being restricted in modulus to 2π. In addition, interferograms from dual pass systems, such as the ERS system, contain errors as a result of uncertainties in the position of the satellite, uncertainties made worse by the relative short (5 cm) wavelength of ERS SAR. To remove the ambiguity and errors requires control heights distributed throughout the 100 km $\times$ 100 km region of the image. High resolution (100 m) altimetry could provide a very important source of such spot heights globally.

3. Research Objectives

3.1. Primary Objectives

The primary research objectives of the Earth Explorer Topography Mission are as follows:

- Determine the annual and seasonal sea ice thickness and roughness climatology, permitting improved understanding and parameterising in global climate models of ocean/ice/atmosphere heat, momentum, water and salt fluxes.

- Determine the seasonal and annual fluctuations of land ice elevation including the climate-sensitive ice sheet margins, ice caps and glaciers, permitting a closure of the cryospheric component of the ocean mass budget.

- Investigate high latitude circulation and its interaction with the marginal ice zone to improve understanding and parameterising in climate models of the ocean/ice/atmosphere coupling and sea level changes.

3.2. Secondary Objectives

The secondary objectives of the Earth Explorer Topography Mission are:

- Determination of sea ice extent, concentration and age, particularly in regions of low concentration where present passive and active microwave observations have difficulty.

- Provide time series of lake and inland water levels.

- Assimilate altimetry data in global prediction models of the ocean, and, should the 200 km geoid be determined, constrain the absolute surface circulation in models.

- Monitor the large-scale and mesoscale ocean variability, the latter providing the meridional eddy fluxes in the ocean to global climate models.

- Contribute to the investigation of coast and shelf interactions between tides, storm surges, shelf currents and the ocean mesoscale and general circulation.

- Provide spot heights of the Earth's land and ice topography that may be used as control points for imaging methods of high resolution topographic mapping, principally SAR interferometry.

- Contribute to climatological observations of cloud statistics and optical depth.

3.3. Uniqueness and Complementarity of the Mission

The Earth Explorer Topography Mission would be the first to focus in an integrated way on four important subsystems of world climate: the sea ice, the ice shelves, the ice sheets and the ocean. Only satellite observations can provide the large-scale, repeated, dense spatial sampling required by the proposed mission.

Sea ice thickness may be measured by a variety of ground-based methods: submarine sonar profiling, moored upward-looking sonar, airborne laser profilometry, airborne electromagnetic techniques, and drilling. These methods have provided the sparse information we do have on sea ice thickness climatology. However, these methods have been unable to even provide a reliable climatological mean.

Ice and glacier mass balance may be measured glaciologically, by differentiating estimates of mass flow and mass accumulation, or geodetically, by measuring the change in elevation of the ice mass with respect to a bed-rock fixed frame. Ground-based surveys, while important and accurate locally, are unable to access the spatial scales required for ice sheet monitoring. In Greenland, airborne survey may provide sparsely sampled geodetic levelling of the entire continent, but it is generally accepted that this task is beyond reach in the Antarctic. The ice sheet margins are presently inaccessible by current radar altimeters, which are unable to deal with the high surface slopes characteristic of these regions.

The fluctuations of the global ocean circulation are uniquely accessible by satellite altimetry on the spatial and temporal scales required, in conjunction with SST (sea-surface temperature), numerical models, and efficient inverse methods and data assimilation techniques. However, the high latitude mesoscale processes need better representation in global ocean climate models.

The mission is complementary to many other Earth observation programmes. Presently, the large quantity of imagery and passive microwave observations of sea ice are limited by lack of knowledge of ice thickness. The addition of thickness observations to programmes of sea ice velocity estimation will enable the mass flux to be determined. The addition of the observations of the ice sheet margins and small glaciers to the time series of radar altimetry of the interior of the Antarctic and Greenland Ice Sheets, will allow the ice sheet and glacier contribution to eustatic sea level to be closed. The coverage of the ocean mesoscale and high latitudes would, if flown concurrently with a TPFO (and possibly a GFO) mission, permit most ocean phenomena with a major influence on climate to be investigated and their interactions studied.

3.4. Timeliness of the Mission

The mission is timely because: the general acceptance of the reality of anthropogenic driven global warming has given accurate predictions of the future development of the Earth's climate on decadal and century time scales an even greater importance than hitherto.

Sea ice, in its influence on planetary albedo, high-latitude exchanges of heat, moisture and freshwater at the air/ice/sea interface, is crucially important in the evolution of climate. The absence of a characterisation of its mass flux and roughness, even as a climatology, seriously limits its proper parameterisation in climate models and the security of their predictions. It is therefore essential that the sea ice mass flux is determined in a timely fashion.

Changes in the mass balances of ice sheets may continue over very long periods of time, and until the secular variation in these balances, due to the long term evolution of the ice sheets in response to Holocene warming, is determined, future changes in sea level on century time scales will remain largely unpredictable. Estimation of shorter term contributions of the ice sheets to sea level is now becoming possible through improved atmospheric models and improved modelling of ice sheet surface balance. However, these predictions are presently extremely difficult to verify. The Earth Explorer Topography Mission will provide a timely verification of these predictions, in those regions of the ice sheets capable of accelerating balance on century time scales.

Monitoring sea-level and ocean circulation changes on monthly to decennial and centennial time scales, coupled with atmospheric and ice observations and models, is also timely. Large international programmes like CLIVAR have started to address these questions. The ocean helps to stabilise the climate by storing CO_2 and redistributing the heat to high latitudes. The Earth Explorer Topography Mission will allow to explore the specific role of high latitudes in ocean circulation and climate, in complement to the tropical programmes planned elsewhere.

Missing the opportunity to fly the Earth Explorer Topography Mission in a timely fashion will prolong the uncertainty that presently exists with predictions of climate evolution on century time scales. The Earth Explorer Topography Mission is focused at climate dynamics that have potentially far reaching consequences on the evolution of the climate on decadal time scales and longer. The prediction of climate change on century time scales depends on accurately modelling trends in planetary albedo, and in the thermohaline circulation. Sea ice has a controlling role in both these processes. The evolution of sea level has human implications as important as any aspect of the climate system. At present, neither of these processes is adequately modelled in numerical models of the century-scale climate. While improvements in resolution may increase the sophistication of their treatment, the observational base that may serve as an objective measure of the notional improvement is missing. In the absence of the Explorer mission, this will continue to be the case.

3.5. Feasibility and Level of Maturity

The sea ice, ice sheets and glacier objectives of the Earth Explorer Topography Mission require high resolution (of order 100 m) measurements of topography that may be differentiated over many years to provide time series of topographic change accurate to a few centimetres over very large areas of the Earth. The most feasible method to achieve this is to use a normal or near normal altimeter with substantially improved horizontal resolution over that of the current generation of radar altimeters of the ERS or TOPEX class. There are two technical possibilities: laser or microwave technology. Both technologies offer feasible methods to achieve the scientific objectives, which have been demonstrated by airborne flights. Of the two techniques, laser technology has the higher level of maturity in Europe, principally through the ATLID development programme. However, the high latitudes, sea ice covered ocean and ice sheets margins have high levels of clouds cover, and the selection of optical technology may significantly reduce the science return of the mission. There is more than one feasible microwave solution to the problem, offering various combinations of synthetic aperture, real aperture and interferometric techniques, and there is more than one possible choice of operating frequency. While less mature than the laser technology, the microwave solution may significantly increase the scientific return.

3.6. Degree of Innovation and Advancement of Capabilities

The Earth Explorer Topography Mission would provide new scientific observations of important processes at the Earth's surface that have not been made hitherto. In turn, new scientific knowledge will arise, and it therefore represents a significant degree of scientific innovation. The increase in latitudinal coverage of the ERS satellites (up to 82°) compared to Seasat and Geosat has given Europe a very significant lead over the United States in polar science. The Explorer Mission would build on and sustain that lead. This is particularly true if the microwave instrument option is taken. In this case, the mission would provide a completely unique capability.

The mission provides a timely extension of European capability because the past decade has seen the development, in the United States and to a lesser extent in Europe, of realisable, cost-effective techniques to provide the high resolution at vertical incidence demanded by the mission objectives. Large improvements have been made in laser technology, particularly in the hitherto difficult areas of power efficiency and cavity lifetime. Existing solutions are available to meet the mission demands of coverage, pulse-repetition frequency and lifetime. The successes of SAR interferometry has led to a much wider consideration of the possibilities offered by interferometric techniques generally (although these have in principal been known for a long time). Techniques for the space realisation of synthetic resolution, combined with interferometric techniques are now reaching maturity, and this mission would offer Europe a timely opportunity to lead the world in these techniques. Whichever the choice of instrument technology, the mission would provide a timely, achievable increase in European instrument technology.

4. Observation Requirements

In considering the observation requirements of the proposed Earth Explorer Topography Mission it is important to note that altimetric observations contain errors at a wide variety of spatial and temporal scales. Some of these are particularly large scale, such as errors in the reconstruction of the satellite orbit, or correction field model drifts in the total electron content of the ionosphere or global atmospheric water content. Others are particularly short scale, such as the variability arising from radar speckle. Whilst recognising the spectrum of errors is a continuum, it is useful to distinguish between very short scale errors and those on a very large scale. In this chapter, short scale errors are characterised by the parameter vertical repeatability, while long-scale errors are characterised by the parameter vertical accuracy. Note that the vertical repeatability is not usually equal to the engineering parameter vertical resolution (or reciprocal bandwidth), because model fitting to the received echo is normally used to improve the vertical repeatability.

4.1. Sea Ice Thickness and Roughness Climatology

The parameter to be measured is the thickness of the sea ice as a function of space and time. Because the ice is floating, the surface roughness is (approximately) linearly related to the thickness.

4.1.1. Spatial and Temporal Scales

Sea ice thickness has two spatial scales of variation. The climatological mean varies slowly on scales of hundreds of kilometres, ranging from 6 m in the Canadian sector of central Arctic falling to 1 m within a 100 km of the ice edge. In the Antarctic, the majority of ice is first year ice of order 1 m thick. In the Weddell Sea, however, multi-year ice is common and the climatological mean is around 3 m. On short, 1 km, scales and smaller, very considerable variations are possible due to wind and current driven ice motion resulting in leads of open water and very thin new ice, and regions with much thicker ice formed by compression such as pressure ridges that may extend to 20 m depth. Polynyas, large areas of open water, may also form due to excessive ocean heat fluxes.

Two scales of temporal variation may also be identified. The climatological mean varies seasonally. At its winter maximum it extends to 50° N in the Northern Hemisphere and to 55° S in the Southern Hemisphere, melting back in the summer minimum to about 70° N in the Arctic and to the shores off Antarctica around 70° S. Ice thickness may vary from 0 to over 20 m. On time scales of days and weeks, very considerable variation can occur at shorter length scales as a result of the advection of the ice.

4.1.2. Measurement Requirements

The instrument resolutions are determined by the need to distinguish ice and open water and by the mission requirement to provide thickness and roughness probability density function climatologies on time scales of months and spatial scales of 50 km. The horizontal resolution is determined by the need to distinguish ice from open water, and studies have demonstrated that 100 m is sufficient for this task. The vertical repeatability is driven by the need to distinguish thin ice, which is the principal control on the ocean/atmosphere heat flux. Ice thicknesses greater than 0.5 m more or less completely shut off the heat transfer. To resolve thin ice thicknesses to 10 cm on an individual floe basis would requires a height sensitivity of 1 cm, since this is the topographic expression of that thickness of floating ice above the ocean. However, if one were to accept a climatological average of the probability density of sea ice over a 50 km × 50 km region, then typically 2500 individual measurements will contribute to the spatially averaged climatology, and one needs then to consider how many measurements are required to accurately determine the probability density function of the ice thickness. For a uniform ice thickness distribution of 0 to 10 m, resolved at 10 cm thickness, a repeatability of 5 cm is required.

The sampling is determined by the need to have sufficient observations to form a 100 km by 100 km climatology. As we noted above, 10,000 spatial samples are required per unit time resolution. 100 metre along track sampling and 10 km across track sampling are sufficient. A trade off is possible between vertical resolution, spatial sampling and spatial resolution of the climatology. With 10 cm vertical resolution, 100 m along track sampling and 50 km across track sampling, a 200 km by 200 km climatology would have an ice thickness resolution of 1.1 cm. The temporal sampling determines the time resolution of the climatology, which needs to be resolved seasonally, and a 1 month revisit time of the 100 × 100 km region is more than sufficient. The temporal sampling also determines the across track spatial sampling. A detailed trade-off is required.

The spatial coverage is determined by the presence of sea ice. This can occur between 50° and 90° of latitude. A truly polar orbit is desirable. The Fram Strait is a key area to monitor thickness because this is where most of the ice export from the Arctic to the sub-polar Atlantic takes place, and coverage of the areas to the north of Greenland and the Canadian Archipelago is important because this is where the thickest ice in the world of 6-8 m is found. A sun-synchronous platform is acceptable. The temporal duration is determined by the requirement to trace the time evolution of the climatological mean. For sea ice, which has a large interannual variability, this requires long time series. Therefore a mission of 5 years is required, preferably with repeated mission observations.

There is no local time requirement. Geolocation is required to a few hundred metres. The measurement is differential and there is no requirement for absolute heights.

4.2. Ice Sheet and Glacier Elevation

The quantity to be measured is the height of the surface of ice sheets and glaciers above a global ellipsoid as a function of position and time.

4.2.1. Spatial and Temporal Scales

In simple terms, the change in elevation of ice sheets and glaciers arises due to accumulation and ablation processes that are principally determined by atmospheric humidity, temperature, wind speed and radiation balance, and the flow of ice under gravity resisted principally by shear stresses deep within the ice or at the bed, or, possibly, resisted by longitudinal stresses transferred from down stream obstacles. These processes give rise to different spatial and temporal scales of behaviour.

Changes arising from flow on large ice sheets may be largely expected to be a secular variation on 100 year time-scales. Unsteady flow is generally expected on ice sheets to have long time constants (1000 years or larger) and effect large areas. Typical of such changes are the effects of the Holocene warming on shear stresses deep in Antarctic and Greenland Ice Sheets. More rapid changes in flow may occur due to bed hydraulics, such as have occurred on Ice Steam C in West Antarctica, which appear to be quite rapid, possibly as quick as a decade. However, this is the exception rather than the rule. The magnitude and spatial variation of this secular term is unknown for the Antarctic and Greenland ice sheets, but is certainly less than 3 cm yr^{-1}. Generally one may also expect it to differ from drainage basin to drainage basin, which may have different climate and bed mechanics. On ice-caps and glaciers, episodic unsteady flow may develop over several months during surges, such as occurs in Alaska and Spitsbergen in the Arctic, with longer, decadal intervals of steady flow. The spatial scales of these flows is small compared with ice sheets, typically of order 10 km, although the changes may be quite large, with drainage basins being drawn down by several metres of water equivalent.

Atmospherically driven processes can occur over time scales of days to many years. Accumulation occurs principally in the winter months with ablation characterising the summer months if the temperature is high enough. Temporal variability is very much higher at the margins of Ice Sheets, which are strongly influenced by storm tracks, than in the high interiors, where the precipitation is more diffusely spread throughout the year and much smaller. In Antarctica, very little surface ablation occurs, and the precipitation and accumulation are similar. Typical rates are 5 cm yr^{-1} of water equivalent in the interior, rising to 1.5 m yr^{-1} at the margins and on ice shelves. The spatial variability of the accumulation is not well known but is generally assumed to be spatially non-stationary. An extremely useful goal for the Earth Explorer Topography Mission would be to characterise this on scales of 100 km. On Greenland, ablation processes are equal to calving in importance. Typical variations in height can be several metres at the equilibrium line (i.e. locus of points for which the net annual accumulation is zero).

4.2.2. Measurement Requirements

The instrument resolutions are determined by the need to obtain adequate signals in regions of high surface slopes, and mission requirements are to provide change measurements of the ice sheet margins and smaller ice caps and glaciers. The elevation errors arising in normal incidence altimetry are dominated over regions of high slopes due to pulse spreading and loss of signal power. This is why the present, pulse limited altimetry systems provide no usable change measurements in regions of significant topography. A significant improvement is possible only by an order of magnitude decrease in the horizontal resolution, and a transfer from pulse-limited to beam-limited operation. This requires a horizontal resolution of order 100 m. The vertical repeatability is determined by the area of which mass balance measurements are required. For the ice sheet margins, 100 km by 100 km is sufficient. An aerial averaged accuracy of 5 cm per month is required to resolve seasonal fluctuations in accumulation. Change measurements are made at crossing points of the satellite orbits, and the aerial averaged vertical error therefore depends on the quotient of the individual vertical repeatability and the square root of the number of cross-overs in the 100 km × 100 km area. Assuming a cross over density of 4 within the 100 km by 100 km resolution cell per month, a vertical repeatability of 10 cm is adequate.

The sampling is determined by the need to have sufficient observations to form a 100 km by 100 km climatology. As we noted above, the observations are made at cross-over points of the satellite orbit, and at least 4 are required per 100 km by 100 km area with a vertical repeatability of 10 cm. A trade off between spatial sampling per unit time resolution and the vertical repeatability is possible. If the vertical repeatability is increased to 50 cm, 100 cross-overs per 100 km × 100 km area are required. The temporal sampling determines the time resolution of the accumulation, and determines the cross-over density per time resolution, (i.e. the number of cross overs per unit area per repeat interval). With a temporal resolution of 35-days, the number of cross-overs in a 100 km × 100 km cell is 8 at 63°, the southern limit of the Greenland Ice Sheet, for a sun synchronous platform. A repeat of 70 days would raise this to 32 cross-overs. Repeats longer than 70 days would increase the cross -over density, but only at the expense of failing to resolve the seasonal cycle.

The spatial coverage is determined by the high latitudes of the large ice sheets, which range from 63° of latitude and higher. Smaller ice bodies can occur anywhere on Earth if the elevation is high enough. A truly polar orbit is desirable. A sun-synchronous orbit, limited in latitude to 82° would prevent coverage of central Antarctica. While the accumulation in this region is small and of limited significance, coverage to 86° would permit the inclusion of the active West Antarctic Ice Streams. A sun-synchronous platform is therefore acceptable but not ideal. A truly polar orbit has no cross-over locations. While in principle change measurements are possible along repeated satellite tracks, the high, and unknown surface slopes of the ice sheet margins will introduce an extremely tight specification on the across-track location of the observations, possibly as small as 100 m. We doubt the technical feasibility of achieving this. Therefore we do not request a truly polar orbit. The temporal duration is determined by the requirement to determine the time evolution of the mass balance. The interannual variability is known from core data to be approximately 25% of the accumulation, and calculations have shown (Wingham 1995) that of order a decade of observations is required. Therefore a mission of 5 years is required, preferably with repeated mission observations.

There is no local time requirement. Geolocation is required to better than the horizontal resolution. The elevations must be made relative to a reference frame fixed to within 2 cm relative to a ellipsoid.

4.3. High Latitude Circulation

The measurement quantity is the ocean topography above a reference ellipsoid.

4.3.1. Spatial and Temporal Scales

The high-latitude circulation of the ocean is composed of a relatively weak mean circulation, constrained by the coasts, and of relatively small-scale variability linked to fronts, eddies, and the meandering of mean currents. The Rossby radius at high-latitudes is small, of the order of 5 km. Typical spatial scales associated with the mesoscale variability are in the range 200-50 km at mid-latitudes and 50-5 km at high latitudes. Typical temporal scales at mid- and high-latitudes are weeks to months. Regimes vary over longer time scales, seasonal to interannual. Expected amplitudes for mesoscale eddies and meanders are in the range 5-30 cm, down to a few centimetres for high-latitude fronts.

Coastal and shelf processes typically follow the geometry of the continental margins, with extended length scales parallel to the coast and shorter (1-10 km) scales perpendicular to the coast. The dynamics of coastal regions are complicated, and much of the details of the coupling between the tides, storm surges, coastal currents and the deeper ocean has yet to be worked out. Temporal scales are typically considerably shorter than those of the open ocean, of order days to weeks.

4.3.2. Measurement Requirements

The instrument resolutions are determined by the requirement to determine the ocean variability, which has a height expression of order cm at 10 km scales. At high latitudes, the mesoscale signal is weaker than at mid-latitudes, and the uncorrelated noise starts 'eating up' the smaller-scale signal. The performance needs to be rather better than the TPFO specifications with regard to vertical repeatability. A specific study is required to further refine the range error there, which may lead to further reduce the noise specification. Here, we will state that the vertical repeatability should be less than 3 cm with a horizontal resolution of 10 km.

The sampling is determined by the need to sample the high latitude mesoscale and if possible the processes at the continental margins. A cross-track distance of 15 km or better at 75° latitude is required. This value is acceptable for high-latitude mesoscale provided that space-time interpolation methods are applied to the data. Coastal and shelf processes may have time scales of a few days or a week, and short scales perpendicular to the coasts. These latter cannot be met by a single satellite. With these constraints, a sun-synchronous 35-day repeat cycle is adequate, although it may not be optimal. It provides the spatial sampling required at high latitudes and the temporal sampling required for the ocean mesoscale. The measurements are made by differentiating along track profiles, and these differences will contain changes in ocean topography, and differences in the geoid due to any across-track variation in the geoid. The satellite ground tracks must be repeating, because the geoid spectrum stays red up to the ocean synoptic scales, and cannot be determined down to those scales by a mission like the Earth Explorer Gravity Field and Ocean Circulation Mission. The mesoscale geoid error at the mesoscale will be large, even if the above mentioned mission flies. Given a sampling strategy, the ground track repeatability should be better than +/-1 km in the cross-track direction at the equator (Minster et al., 1993). In addition, repeats longer than 35 days are undesirable, because the measurements will have to be referred to a long-term average which would not be determined properly if the repeat was too long.

The spatial coverage is determined by the requirement to include the ice edge and some of the marginal ice zone in both hemispheres, which means a latitude coverage of 80°. The temporal duration should be initially considered for a period of 3-5 years for the demonstration objectives listed above.

There is no local time requirement. Geolocation is required to better than the horizontal resolution. The elevations must be made relative to a reference frame fixed to within 2 cm relative to a global ellipsoid.

4.4. Observation Requirement Summary

The requirements of the Earth Explorer Topography Mission are summarised in Table 4.1.

	Sea Ice	Land Ice and Glaciers	High Latitude Circulation
Horizontal Resolution	100 m	100 m	5 km
Vertical Repeatability	5 cm	10 cm	3 cm
Vertical Accuracy	No requirement	2 cm	2 cm
Across Track Sampling	50 km at 65° latitude	30 km at 65° latitude	15 km at 75° latitude
Temporal Sampling	1 month	2 months	10-35 days
Mission Duration	5 years	5 years	5 years
Mission Revisit Time	5 years	5 years	5 years
Minimum Latitude	50°	0°	0°
Desired Maximum Latitude	90°	90°	82°
Acceptable Maximum	82°	82°	82°
Local Time	No requirement	No requirement	No requirement

***Table 4.1**. Observation Requirements for the Earth Explorer Topography Mission.*

4.5. Data Products

The basic observations of the mission are (i) The geolocated, returned echo power as a function of delay time at 100 m intervals along the satellite track. The echo delay time will be fully corrected for instrumental and atmospheric delays, and the echo power will be fully corrected for instrumental, travel path and atmospheric losses; and (ii) A derived surface elevation at 100 m intervals along the satellite track.

A very large number of higher level products may be derived from these basic products. All of these may be gridded at a variety of spatial and temporal resolutions. It is important to note that, while the details of the higher level processing do require further investigation, there is no serious doubt as to the feasibility, as considerable experience exists with satellite observations of lower resolution, and airborne measurements at higher resolution.

For sea ice, the surface topography of sea ice can be quantified by various statistical measures such as probability distribution functions (PDF) of surface elevation, or ridge height frequency distributions. With a 100 m footprint, it should be possible to resolve the height difference between multiyear ice, first year ice, thin ice and ridged areas larger than a few 100

m. However, it is presently unclear whether individual ridges can be identified with 100 m resolution. The main requirement is to obtain averaged height estimates which can be used to construct PDFs along and across the satellite tracks. The measured elevations will contain fluctuations due to the geoid, the ocean topography and the sea ice itself. The sea ice signal will need to be isolated by high pass filtering of the along-track data, although the spatial cut off of this filter will need further examination.

For land ice, the along-track elevations, corrected as far as possible for surface gradients, are the principal topographic product. For ice elevation change, differentiating repeated along-track elevations is compromised, because the variation due to surface gradients introduces unacceptably large errors, unless the locations of the observations can be held to within 100 m, and extremely difficult requirement to meet technically. Elevation change is therefore performed at the crossing points of the satellite orbit. Experience with pulse-limited altimetry suggests this is possible only by a detailed examination of the echo pulse profiles at the crossing point. The precise technique will require greater investigation when some experience of processing high resolution echoes has been obtained.

For the ocean, the numerous, well-known techniques of along- and across- track elevation processing are available. The space-time reconstruction of individual mesoscale and large-scale features will require the use of mapping and/or inverse techniques. If a geoid with sufficient accuracy and spatial resolution is available, the absolute sea-surface topography and its mean will be accessible.

4.6. Timing of the Mission

The timing of the mission may also greatly increase the science return of the mission. The situation is summarised in Table 4.2.

Sea ice velocity, ice type classification and quantification of freezing and melting will be extensively investigated with SAR data from ERS-2 (1995), Radarsat (1996) and ENVISAT (1999), increase the demand for ice thickness and ice roughness data from satellites. The combination of ice thickness, ice velocity, ice age and estimates of density and salinity will permit the sea ice mass flux and freshwater flux to be estimated. The Earth Explorer Topography Mission should therefore fly in parallel with a high-latitude SAR mission.

The EOS Laser ALT (US ICESAT) is intended for launch in 2003. This mission will initiate laser observations of the ice sheet margins and sea ice. The development of an understanding of the seasonal and interannual fluctuations of both sea ice and ice sheet precipitation will be greatly aided by flying in series with the EOS Laser ALT mission with a period of overlap for cross calibration. The mission lifetime is assumed limited to two years based on the expected operating life of the laser. To ensure overlap with this mission the launch windows of 2002 or 2004 are therefore suitable.

Sensor	Science Gain	Timing	Satellite	Launch Date
Pulse Limited Altimeter	Coastal Processes High latitude ocean dynamics	In parallel	ERS-1/2 GFO-1 ENVISAT TPFO	1991/1995 1996 1999 2000
SAR	Sea ice velocity, concentration,age, sea ice mass flux and freshwater flux	In parallel	ERS-2 Radarsat ENVISAT	1995 1996 1999
Gravimeter	Absolute circulation	Not critical	CHAMP Earth Explorer Gravity Field and Ocean Circ. Mission	1999 ?
Laser Altimeter	Sea Ice and ice sheet balance climatologies	In series with overlap	EOS Laser ALT	2003

***Table 4.2**. The additional benefit of launching the Earth Explorer Topography Mission in parallel and in series with other satellite sensors. The years 2002 and 2004 are natural windows of opportunity for the Earth Explorer Topography Mission.*

It seems likely that the continued flight of a TPFO class altimeter will occur. The ENVISAT RA-2 altimeter will fly in 1999, the continuation of the GFO series may also be decided beyond the year 2002 with an improved design with respect to GFO-1. The ocean objectives of the Earth Explorer Topography Mission and its contribution to knowledge on climate and accurate forecasts will be greatly enhanced by the flight in parallel with RA-2, TPFO and GFO. In addition, these missions flying together with complementary orbits would seem to have sufficient sampling capabilities to monitor coastal processes, especially at mid- and high-latitudes where the ground tracks intersect the coasts with a greater angle. The Earth Explorer Topography Mission should therefore fly in parallel with one or more altimetry missions. Other elements to be taken into account for climate modelling and prediction are the maturity of data assimilation techniques in global, coupled models, and the involvement of major actors such as ECMWF and the national Meteorological Offices.

A launch date of 2002 or 2004 are therefore recommended, the earliest opportunity to obtain coincident SAR and altimetry coverage, and permitting overlap with the US ICESAT mission. If these windows of opportunity are missed, a launch date should be chosen subject to developments in the future deployment of SAR missions.

4.7. Extent of Fulfilment of Research Objectives

4.7.1. Dependence on Instrument Selection

There are two instrument alternatives that may fulfil the requirements for surface elevations with of order 100 metre resolution. These use either optical or microwave techniques. The selection of the instrument may have significant impact on the achievement of the science objectives, and therefore needs to be considered carefully. The possible impact of the instrument selection arises because the atmosphere may have a significant impact on the achieved spatial and temporal sampling.

Optical instruments have severe limitations due to cloud cover in sea ice areas and the ice sheet margins. Cloud climatologies predict that from 70° to 80° South, cloud cover affecting a laser instrument will exist between 50-70% of the time, and around 50% of the time at a similar latitude in the Northern Hemisphere (Figure 4.1). Such cloud cover has a severe impact on ice sheet change measurements, where two observations are required at a cross over point. On average, therefore, it may be expected that the probability of obtaining a cross-over will be around 10%. Although the density of cross-overs may be increased by increasing the orbit repeat period, temporal resolution will be lost. Calculations indicate that, with such a loss, it will not be possible to resolve a seasonal signal in ice sheet accumulation at 100 km × 100 km resolution. Therefore, if an optical instrument is selected, a significant loss in scientific return may occur.

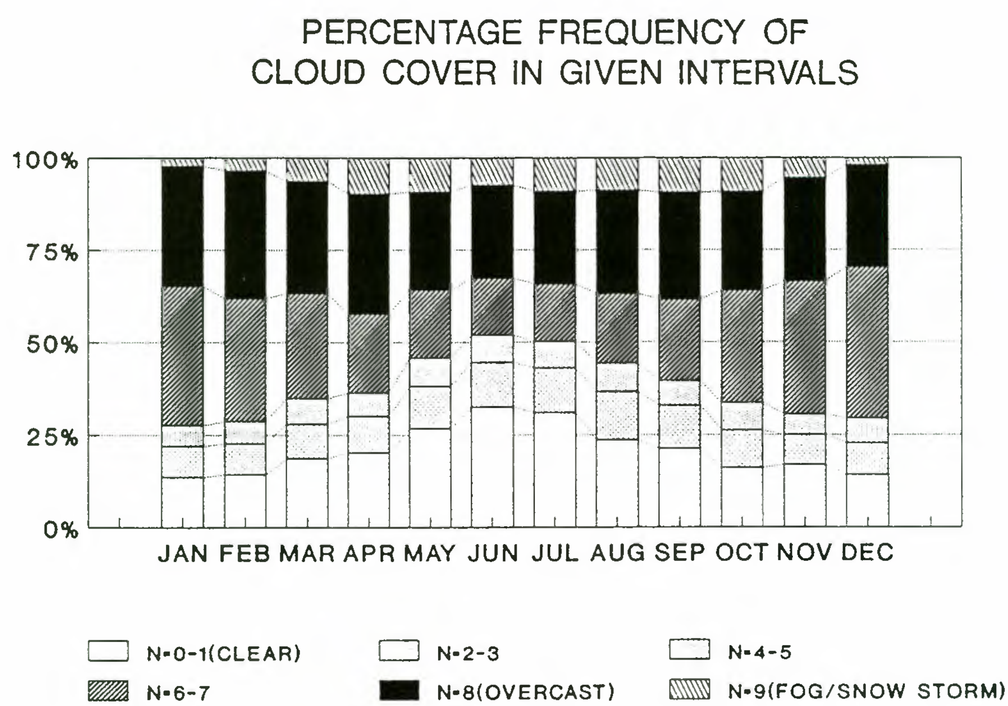


Figure 4.1. *Cloud cover statistics from the Halley Station in Antarctica from 1957 to 1989 (Hanssen-Bauer, 1992).*

Over sea ice, the situation is less critical, because the observations are not limited to cross-overs, and because differentiating between repeats is not essential. Good laser profile data of the ice surface can only be obtained in 10-50% of the days, depending on season and area. The most cloudy areas will be the ice edge zone, whereas the interior of the ice pack, say 100-200 km from the ice edge, the number of cloud free days is up to 50%, especially in late winter. The summer is the most cloudy period when low stratus clouds can be present over 90% of the time. It is to be noted that cloud cover has significant seasonal variation, and this may also result in seasonal biasing of long-term means.

Microwave instruments are largely immune from problems due to cloud, although attenuation and path delay does become increasingly significant above 10 GHz.

Ocean altimetry depends for its accuracy on the spatial averaging over the echo footprint of current, pulse-limited altimeters. The averaging is important, because it greatly reduces fluctuations in the elevation caused by individual waves (strictly, individual scatters). (Note that this is not the same fluctuation resulting from radar speckle). Measurements with a higher spatial resolution will contain fluctuations due to this effect. If a single beam instrument is used, it will not be possible by post-integration to obtain the same degree of fluctuation reduction. The magnitude of this effect needs careful consideration. This may considerably increase the requirement for the vertical repeatability of the measurement. Therefore an instrument design capable of real-time or post deresolution is highly desirable.

4.7.2. Dependence on Sampling Selection

The mission objectives cannot be completely achieved with the temporal and spatial sampling and coverage characteristics of a single satellite. One needs to consider the consequences of selecting a single satellite mission, or of using more than one satellite.

For a single satellite, the principal choices are the latitudinal coverage, the orbit repeat period and the orbit altitude. In our view, a sun synchronous (82° latitude coverage) platform is a good compromise between the ice and the ocean goals. It provides coverage of most of the ice sheets, and most of the variability of sea ice cover. A higher inclination is desirable to include the Arctic sea ice, West Antarctic ice streams and southern Ross Ice Shelf. However, with such a latitudinal coverage, the sampling of the mid latitude mesoscale ocean becomes zonally poor.

The orbit repeat period is not critical for sea ice, and indeed a drifting orbit is acceptable. If a laser system is selected, the repeat period should be extended to 140 days or a drifting orbit to ensure an adequate cross-over density to resolve even annual fluctuations in ice sheet mass. If a microwave system is selected, the repeat period should be shorter, but should not be less than 35 days, or the low cross-over density will make it difficult to resolve seasonal fluctuations in ice sheet mass. For the ocean mesoscale, a repeat period longer than 35 days results in a temporal under sampling, and makes the formation of longer term means difficult. The satellite altitude is principally determined by engineering constraints.

A second satellite is likely to be necessary if a laser system is selected. As noted above, this system should have a long repeat or drifting orbit, and in this case the ocean science return are greatly diminished. Should the mission be achieved this way, a latitudinal coverage of 86° should be selected for the ice satellite. Note that a true polar orbit should not be selected as such an orbit has no cross-overs.

4.7.3. Uncertainties and Need for Further Research

At the time or writing, some areas where further studies are necessary have been identified. These uncertainties do not effect the feasibility of the mission, for which adequate knowledge and experience already exists. However, some open questions remain which need closing as part of a mission Phase A study. These are:

The selection of optical or microwave instrumentation. There are two aspects requiring closer investigation. Firstly, the cloud loss problem for the laser system needs very careful analysis for the reasons described in Section 4.7.1. Secondly, the performance of a microwave system over ice sheet topographies and sea ice needs to be studied carefully as a function of resolution. This will probably require numerical simulation of the echoes from realistic target geometries and scattering models.

The vertical repeatability of ocean measurements. The high latitude mesoscale structure has small spatial scales and is characterised by low potential energy storage. The height variability may significantly reduce the observable phenomena. Variability will result from 'speckle' (a consequence of incoherent imaging), and from reducing the area averaged by a high resolution instrument. This needs closer investigation.

The definition of sampling strategies for coastal processes. Coastal ocean dynamics are characterised by small space and time scales, anisotropy, the dynamical coupling of open-ocean currents and eddies with tides and storm surges, and possible errors due to sea-state. Studies are currently ongoing to explore the sampling and data redundancy issues associated with tides and surges in coastal areas, with an emphasis on the understanding of the processes. For instance, the TOPEX/POSEIDON-ERS tandem may prove valuable in some stretches of the world coasts. Such investigations must be pursued to make the most of future tandem opportunities.

5. Mission Elements

5.1. General

As will be recognized in this chapter, there are two core solutions for the Earth Explorer Topography Mission elements which can meet the observations requirements discussed in chapter 4.

5.2. Space Segment

The definition of the space based elements of the Earth Explorer Topography Mission takes into account the observational requirements established in chapter 4 and the implementation possibilities as summarised in Table 5.1.

Mission Elements	Cryosphere	Ocean
Observation principle	Beam limited altimetry	Pulse limited altimetry
Instrument options	Laser altimeter	Pulse limited altimeter, e.g. RA-2
	Microwave, beam limited altimeters	Microwave, beam limited altimeters, either in pulse limited operation or supporting 'deresolution'
Coverage	86° preferred, but 82° acceptable if ice and ocean missions are combined and sampling strategies are compatible	82°, sun synchronous orbit acceptable
Sampling	Laser option requires drifting orbit or very long repeat cycle for dense grid of observations	Track repeatability required, long repeat cycle though not longer than 35 days.
	Microwave option does not require long repeat cycle, but at least 30 days	

Table 5.1. *Observation Requirements and Options*

The criteria for the definition of the implementation options are derived from the above table:

- A combined ice-ocean mission is possible if the 35 day repeat cycle is adopted; the orbit may be sun-synchronous. As microwave beam limited altimeters can be operated also in pulse limited mode, the combined ice-ocean mission can be implemented with only one instrument.

- In a dual satellite scenario the ice observations are performed by means of laser altimetry. In this case, the Ice Topography Explorer, not subject to the constraints imposed by the ocean part of the mission, should be flown in an orbit providing latitude coverage up to at least 86°. Ocean observations are carried out by the Ocean Topography Explorer flying in a 35 day repeat orbit with a conventional pulse limited altimeter such as the ENVISAT RA-2.

The criteria outlined above are illustrated in Table 5.2. The selection of the mission scenario should be based on a trade off to be performed as part of the phase A study.

Implementation	Mission	Core Payload and Orbit
Dual satellite	Cryosphere	Laser altimeter. High inclination orbit providing latitude coverage up to at least 86°.
	Ocean	Pulse limited altimeter. Sun synchronous orbit, 35 day repeat
Single satellite	Combined Ice and Ocean	High resolution microwave altimeter with 'deresolution' for ocean mode. Sun synchronous orbit, 35 day repeat cycle.

***Table 5.2**. Space Segment Elements*

In addition to the core payload the following ancillary instruments are required:

- A microwave radiometer (MWR) with at least two channels for atmospheric corrections to be implemented on satellites with microwave altimeters.
- A GNSS receiver for precision orbit determination. This instrument could at the same time perform atmospheric soundings (ESA, 1996).
- A laser retroreflector as back-up for the GNSS receiver.

5.3. Ground Segment

The ground segment includes the following elements:

- A Command and Data Acquisition Element (CDAE) located at a suitable northern European latitude to process the received data to Level 0.
- A Mission Operations and Satellite Control Element (MSCE), also controlling the ground segment as a whole.
- A Processing and Archiving Element (PAE) to process the data provided by the CDAE

to Levels 1a and 1b and to provide archiving facilities.
- A Science Data Centre (SDC) will process data to Level 2 and above.

The Earth Explorer Topography Mission assumes the availability of data from other missions as outlined in section 4.6.

5.4. Ground Observations

GOOS has established a comprehensive programme of ground based observations, which can be used in support of the Earth Explorer Topography Mission. Moreover, complementary cryospheric observations by means of airborne lasers and microwave radars, submarine sonars, upward looking moored sonars and sporadic drilling can be used for instrument calibration and data validation.

6. System Concept

6.1. Introduction

The Earth Explorer Topography Mission would consist of two parts, the space and the ground segments. While several alternatives have been identified for the former, which would in different ways meet the observation requirements as set forth in chapter 4, the latter could be based on the Agency's existing infrastructure.

Two mission scenario alternatives have been identified in response to the research objectives. The first one is a single satellite scenario with one altimeter to cover ocean and ice observations. Compromises would have to be accepted in this case in terms of latitude coverage and sampling strategy. The second alternative employs two satellites, one being optimised for ocean, the other for ice observations.

Several altimeter concepts exist which could meet the observation requirements. They all differ significantly not only in their design and interface requirement but also in the resulting mission profiles. Consequently different satellite configurations will result from the choice of the instrument.

6.2. Payload

6.2.1. General

The observation requirements call for an instrument horizontal resolution in the order of 100 m for ice measurements and 5 km for ocean measurements with a vertical repeatability below 10 cm in both cases. This is to be understood as a mission and not only as instrument or satellite requirement.

Altimeters can be designed using optical or radiofrequency techniques. Only one design concept has been identified for the optical version, a laser range finder, which is limited to cryospheric observations. Several alternatives exist for the microwave instruments with different capabilities. These are summarised in Table 6.1.

If topographic features are to be resolved with sufficient repeatability for ice observations a beam limited microwave instrument must be used as opposed to a pulse limited altimeter. A classical pulse limited radar altimeter could be used if only ocean observations need to be performed.

The laser altimeter would offer the required spatial resolution, but its observations are hampered by the presence of clouds. This constraint does not exist for microwave instruments, but their spatial resolution will be coarser dependent on beam or pulse limited concepts.

Altimeter Concept	**Functional Principle**	**Possible Application**
Laser	Beam Limited	Cryosphere
Classical (*)	Pulse Limited	Ocean/Ice sheet with slopes ≤ 1°, sea ice edge
High Resolution µwave	Beam Limited	Cryosphere/Ocean
	Interferometric	Cryosphere/Ocean
	Synthetic Aperture Altimeter	Cryosphere/Ocean

Table 6.1. *Summary of the different altimeter concepts, their functional principle and possible applications to be discussed in chapter 6. (*) Under classical altimeter concepts the ERS, ENVISAT, T/P and the planned TPFO and GFO are included.*

Whilst a profiling instrument would a priori satisfy the observation requirements, use of a scanning version would significantly improve signal statistics, however at the expense of higher complexity. This option exists only for the microwave altimeters as an imaging laser altimeter would put excessive demands on satellite resources without a substantial gain in mission return. A GNSS receiver would be part of this mission to provide high accuracy orbit determination data and, as an option to perform sounding of the atmosphere by means of occultation profiles of navigation satellite signals; details are found in the relevant mission assessment report (ESA, 1996).

6.2.2. Laser Altimeter Concept

Instrument Objectives

The requirement for the laser altimeter is to provide elevation profiles of continuous ice sheets and roughness profiles over sea ice at horizontal resolution of about 100 m in a continuous sub-satellite track with vertical repeatability of at least 5 cm on ice or snow surfaces with a slope up to a few degrees.

Instrument Description

The instrument requirements could be largely met by an altimeter based on a Nd:YAG laser operating at the fundamental wavelength of 1.06 μm. This wavelength is preferred over the second harmonic at 532 nm by comparing their performances, taking into account all elements of the accuracy budget. Measurement of the range between target and satellite is performed by timing of the return pulses scattered by the surface. Contrary to conventional pulse-limited radar altimeters, laser altimeters emit short pulses of the order of 10 nsec in a narrow beam ensuring beam-limited operation. The range to the target is generally measured by calculating the position of the centroid of the return pulse.

The laser transmitter emits pulses with an energy of 50 mJ at a rate of 70 Hz (currently baseline). The pulse duration is about 10 nsec achieved by the use of a short-resonator laser. The beam divergence is 0.15 mrad corresponding to a footprint diameter of 100 m from an altitude of 650 km. The footprint is large enough to ensure that operation of the instrument is eye-safe for casual observers using binoculars. The footprints are contiguous by choice of the pulse repetition rate.

As the laser has a limited service life, a second unit should be flown in cold redundancy to ensure the lifetime of 5 years. Alternatively, a single laser with redundant Nd:YAG slabs and laser diodes could be a more compact solution. It is interesting to note that the lifetime of the laser would be prolonged by the operation of the altimeter only over high latitude regions covered by ice sheets and sea ice.

As the laser has an inherently low efficiency (between 3 and 5 %), the dissipation of the heat is a critical area of the laser design and of the thermal control of the instrument as a whole. Heat pipes directly connected to the pump chamber or a two-phase cooling loop can be implemented to transfer the thermal energy to an external radiator.

The laser beam is transmitted to the target through an optical system independent of the collecting telescope. The diameter of the beam at the exit is about 5 cm. The laser beam is co-aligned with the collecting telescope which is a compact Cassegrain design with a primary mirror of 90 cm diameter. The imaging quality requirements are not very stringent as the telescope only collects energy. Low-weight materials like Beryllium, SiC or C/SiC can be considered for the telescope to minimise instrument mass. As the telescope is fixed, low mass is not an absolute requirement and so a somewhat heavier but technologically safe design using Zerodur mirrors and a Carbon Fibre Reinforced Plastic (CFRP) structure is also possible.

With the telescope pointing at nadir, no lag-angle compensation mechanism needs to be used. The field-of-view of the receiving optics should only be larger than the beam divergence, increased by the point-spread-function of the optics and a margin to accommodate the residual misalignment of the laser beam with respect to the telescope.

The alignment of the laser beam with respect to the telescope's line of sight is essential to minimise its field-of-view and hence the received solar background. In addition, knowledge of the absolute pointing direction of the laser beam is required for the location of the footprint on ground. Accuracy requirements are in the order of 2 arcsec to limit the range error on surfaces with slopes up to 3°. Accuracy depends critically on the alignment of the laser beam with the attitude reference frame.

The detection chain uses an uncooled Silicon avalanche photodiode located at the focal plane of the telescope. Narrow-band filters with a bandwidth of about 10 nm are used to reject solar background. The signal is sampled at a rate of 250 MHz with a 8-bit A/D converter, corresponding to a range sampling interval of 60 cm. The return pulse extends over a few samples and the system is designed so that its peak SNR is at least 10 over a flat ice or snow surface observed in clear sky. The centroid of the samples is used as an estimate of the return time of the pulse and hence of the range to the target. In these conditions, the single-shot ranging accuracy of the instrument is about 6 cm for a flat target area.

Several contributions to the estimated mission error budget have been identified as listed in Table 6.2. In addition to biases related to orbit determination and timing accuracy as well as atmospheric effects, the main errors are caused by the surface roughness, combined with attitude errors. Surface roughness and slope broaden the return pulse and decrease the peak SNR, reducing the range estimation accuracy. If the pointing direction is not known with high accuracy (2 arcsec) , surface slope biases the altitude measurements. The same effect can be observed in the presence of non-homogeneous targets (for example ice and rocks in the same footprint).

	Surface Slope 0 degree	**Surface Slope 1 degree**	**Surface Slope 3 degrees**
Instrument Errors			
Range repeatability, single shot	6 cm	7 cm	11 cm
Knowledge of altimeter reference	0.5 cm	0.5 cm	0.5 cm
Variability of reflectivity	0	3 cm	9 cm
Platform Errors			
Radial orbit error	4 cm	4 cm	4 cm
Horizontal orbit error	0	0.2 cm	0.5 cm
Attitude determination and alignment (2.7 arcsec)	0	15 cm	45 cm
Atmospheric Errors			
Surface pressure (< 10 mbar)	2 cm	2 cm	2 cm
Surface temperature (< 25 K)	0.5 cm	0.5 cm	0.5 cm
Other			
Clock etc	1 cm	1 cm	1 cm
Total Range Error (rss)	8 cm	18 cm	47 cm

Table 6.2*. Laser Altimeter Estimated System Error Budget*

Instrument Interfaces

The accommodation of a laser altimeter on a dedicated small satellite is possible as the instrument can be an integral part of the structure, resulting in mass and volume savings. Electronic boxes can be accommodated inside the satellite. The thermal control design is also more efficient by the flexibility offered by an integrated approach of the satellite-instrument system.

Instrument mass has been estimated as about 60 kg. The power drawn by the instrument from the satellite supply would be about 215 W for full operation and 70 W in stand-by mode. The data rate is about 100 kbps.

Instrument Development Status

The laser altimeter exists as a conceptual design only. However similar instruments have already been developed (MOLA on Mars Observer) or are planned (EOS Laser ALT). The technologies used in this type of laser altimeter are very similar to those used in the backscatter lidar (ATLID) of the Earth Explorer Earth Radiation Mission (ESA,1996). In particular, the laser transmitter, which can be considered the most critical subsystem of the instrument, can be based on ATLID technology. Other subsystems could be developed without major risk.

6.2.3. Pulse-limited Radar Altimeter Concept

Instrument Objectives

The radar altimeter shall determine the range between the satellite and the sea surface. It must be supported by a microwave radiometer (MWR) for the correction of atmospheric effects.

Instrument Description

The observation requirements would be met by a design based on the RA-2 instrument, i.e. a double frequency design operating in Ku-band (13.6 GHz) and S-band (3.2 GHz). The antenna gain must be greater than 40 dBi at Ku-band and greater than 28 dBi at S-band, for which a reflector with a diameter of 1200 mm is adequate.

Based on ERS and ENVISAT experience, the MWR is assumed as a dual-channel instrument operating in the 24 GHz and 37 GHz bands. The first level estimation of the system error budget is given in Table 6.3

Error Components	Range Error
Theoretical performance	4 cm
Ionospheric correction	0.3 cm
Instrument errors (after calibration)	1 cm
Antenna pointing	0.5 cm
Wet tropospheric correction	1.2 cm
Dry tropospheric correction	0.7 cm
Electromagnetic bias	3 cm
Orbit radial error	4 cm
Total Error (rss)	7 cm

Table 6.3. *Radar Altimeter Estimated System Error Budget*

Instrument Interfaces

The antenna reflector constitutes the driving constraint for instrument accommodation. It needs to be located on the nadir face with an unobstructed field of view to Earth. Instrument mass is 77 kg for the altimeter and 10 kg for the radiometer. The power requirement is 72 W for the altimeter and 20 W for the radiometer.

Instrument Development Status

A reflight of RA-2 as designed for ENVISAT is assumed resulting in a mature instrument. This applies also to the MWR.

6.2.4. Beam-limited 94 GHz Radar Altimeter Concept

Objectives

The instrument would provide elevation profiles with high horizontal resolution over ice and ocean in a beam-limited mode of operation.

Instrument Description

For beam-limited operation, a small beam footprint can only be achieved by increasing antenna size and operating frequency. At a frequency of 94 GHz, a footprint of 350 m can be obtained by using a 4.5 m antenna from an altitude of about 525 km.

A swath of about 5.6 km could be provided with an array of 16 feeds in offset configuration.

The measurement of the range is performed as in laser altimeters. After compression of the return pulse, the centroid of the short echo gives an estimate of the range to the surface. A 16-feed system delivering pulses of 40 μs duration and 10 W peak power at a total repetition rate of 4.8 KHz would have a vertical repeatability of about 5 cm over low-roughness ice. The vertical repeatability could be improved by averaging samples along- and across-track.

Instrument Interfaces

The antenna must be deployable for launch by a small- or medium-size launcher. A foldable antenna concept would be a cylinder of a diameter of 2.1 m and a length of 1.5 m in the stowed configuration. The instrument concept resource requirements are estimated to be about 280 kg and 150 W; the data rate would be about 2.5 Mbps.

Instrument Development Status

The instrument concept is of traditional principle and limited development risk is expected in the radiofrequency and electronic subsystems. However, a certain development effort would need to be devoted to the foldable antenna. Deployable antennas of similar diameter have been manufactured and tested on-ground for telecommunication applications at 38 GHz, but the more severe surface accuracy requirements at 94 GHz and verification of the space deployment would be the development issues.

6.2.5. Interferometric Altimeter Concept

Objectives

High horizontal resolution elevation profiles could be obtained by a combination of synthetic aperture processing with interferometry. The along-track focusing would be performed by coherent synthetic aperture processing, whereas an interferometric technique with two antennas could be used to improve the across-track resolution.

Instrument Description

An interferometric altimeter could in principle be made by adding a second receiving antenna to a pulse-limited radar altimeter at 13 GHz. The additional antenna would be of similar size and would be offset by a short distance in the across-track direction.

Incoherent processing of the echoes received by the antennas would provide a pulse-limited mode of operation for ocean applications with performances similar to those described in Section 6.2.3.

Synthetic aperture processing could improve the along-track resolution to about 200 m. To improve across-track resolution, the use of two antennas permits that the altimeter is operated as a direction-sensing instrument: the phase difference between equivalent range bins of the echoes received by the two antennas gives an estimate of the direction to the reflection point on ground.

The across-track resolution depends on the phase noise performance of the instrument; a horizontal resolution of about 200 m should be achievable.

The principle of operation is based on the assumption that the reflection point on ground is unique in each range bin as the existence of distinct topographic details at the same range produces ambiguities which must be considered in the data processing system.

Instrument Interfaces

The resource requirements are estimated at about 120 kg and 300 W

Instrument Development Status

The interferometric altimeter is only a very preliminary design concept. It can be considered as technically feasible at low risk. However its performances could only be assessed by extensive simulations of its operation over realistic targets of various topography and roughness. The system being critically sensitive to degradations of the phase difference between the echoes, the design of phase-processing hardware and algorithms would therefore need particular attention.

6.2.6. Synthetic Aperture Altimeter Concept

Objectives

Along-track synthetic aperture processing could be used to improve along-track resolution in a high-frequency radar altimeter. A swath could be provided by electronic beam steering.

Instrument Description

The instrument concept would feature a 6 m long antenna oriented across-track. At 37 GHz, the system would provide an across-track beam-limited resolution of about 900 m, from an altitude of 650 km. The along-track resolution could be improved to about 100 m by synthetic aperture processing. A vertical repeatability of 10-20 cm is considered feasible.

Electronic beam steering by phase shifting the radiating elements of the phased-array antenna would be used to provide a swath of a few kilometres.

Instrument Interfaces

The resource requirements have been estimated to about 250 kg and 220 W. The size of the antenna is 6 m (across-track) by 1 m (along-track).

Instrument Development Status

The instrument concept is very preliminary. The feasibility of such a large planar phased-array antenna at 37 GHz with acceptable losses and good phase stability is doubtful at this time. Mechanical and thermal stability of the antenna are also critical. It is thus not recommended at this stage to pursue further the study of this type of altimeter.

6.3. Mission Profile

6.3.1. General

Distinct mission profiles arise from the selection of the mission implementation concept. In the event of a single satellite mission, a microwave altimeter would be flown aboard a satellite in a sun-synchronous orbit.

For a dual satellite mission, the laser altimeter satellite will fly in a high inclination orbit to achieve the required latitude coverage, whereas the radar altimeter satellite would fly in a sun-synchronous orbit.

6.3.2. Orbit Definition

Non Sun-Synchronous Orbit (Laser Altimeter Satellite Concept)

This type of orbit must be used for the laser altimeter satellite in order to cover latitudes up to 86°. This can be achieved by orbit inclinations of 94° or 86°; the former case has been selected because of a smaller change in local solar time.

For an active instrument, performance is strongly related to range. On the other hand the stability of low altitude orbits is affected by drag of the residual air. Orbit altitude is also a function of repeat cycle, which has a marked effect on spatial sampling as the ground track spacing at the minimum latitude of interest determines the number of cross over points per reference area as defined in chapter 4. A suitable compromise is found for an altitude of 652 km. It has to be noted, that for ice observations a long repeat cycle is desirable to increase the number of cross over points.

As the performance of a laser instrument is strongly affected by the presence of clouds, significant spatial oversampling must be applied in order to meet the mission performance requirements. Available cloud statistics suggest that the ice covered areas have a cloud free line of sight of 30 to 40 %. As two orbits are required to establish cross over points only about 10 to 16 % of all data points can be used or in other words oversampling must be in the order of 6 to 10. This can be achieved by increasing, in this case about doubling, the repeat cycle as the track spacing will decrease accordingly. In the extreme case a drifting orbit can be selected.

Sun-Synchronous Orbit (Radar Altimeter Satellite Concept)

For radar altimeters, either serving only ocean or ocean and ice observations, a low orbit should be selected to maximise instrument performance. The orbit repeat cycle should be about 1 month. A compromise has been found as a 524 km orbit with a repeat cycle of 33 days. It needs to be mentioned here that ocean observations require a well defined repeat cycle for which onboard maintenance system is necessary.

A sun-synchronous orbit allows the node crossing time to be selected. A so-called dawn-dusk orbit with node crossings at 0600 and 1800 hours results in a rather simple satellite design because of the limited changes in solar aspect angle.

6.3.3. Communication Scenario

The communication scenario is derived from two constraints: the instrument data rate, as listed in section 6.4 and the choice of the receiving station., which should be located at an as northerly latitude as possible to maximise the ground contact times. For the time being Kiruna has been chosen as the sole ground station; eventually Tromsø or even Svalbard could be also used.

Laser Altimeter Satellite Concept

The data rate of this satellite concept is about 100 kbps. As the instrument does not need to be operated outside the ice covered surfaces its duty cycle results in a data volume of about 200 Mb per orbit.

By using only Kiruna as a ground station not all orbits will be visible for data transfer. Out of the about 15 orbits per day 5 consecutive ones would be without any ground contact time. The onboard recorder has thus to be sized for about 1 Gb. At present the maximum data rate in S-band is limited to about 1 Mbps. As a consequence the total contents of the onboard recorder cannot be downlinked during a single pass and the remaining contents must be deferred to later passes. With the presently available downlink capacity a significant transmission margin is still available, which could be used for increasing the duty cycle of the altimeter for example.

Radar Altimeter Satellite Concept

A classical pulse-limited radar altimeter generates a data stream of about 150 kbps. The instrument should remain in operation continuously throughout the orbit which results in a data volume of 900 Mb per orbit. For a single ground station with 5 blind consecutive orbits an onboard recorder of 4.5 Gb is necessary. Downlinking of these data is not possible in S-band and an X-band transmission system must be employed. The available downlink capacity is 100 Mbps which is more than adequate for this application.

For the high resolution multi beam altimeter, the data rate would increase to about 2.5 Mbps, resulting in a data volume of 15 Gb per orbit and a 75 Gb data recorder will need to be used. This data volume can still be transmitted to ground with the existing X-band infrastructure.

6.3.4. Geo-Location

The sampling strategy being based on the range data collected at the cross over points of the orbits, their location must be determined with high accuracy. The satellite ground track must therefore be determined to an accuracy in order of the instrument's footprint. There are three main error contributions to the location of the footprint: Position along the orbit, attitude knowledge error and timing.

As a geodetic quality GNSS receiver will be flown on the topography mission, the along track position can be determined to an accuracy of several centimetres. Instrument performance over sloping terrain critically depends on attitude knowledge. The requirements are in the order of several arcseconds which can be only met by means of a star camera. This transforms into a typical horizontal location error of about 10 m. A very conservative assumption has been made for the assessment of the location error caused by onboard timing. A 1 ms timing error would result in a position error of about 7 m. All of the error contributions being much smaller than the diameter of the footprint, the location of the cross over points can thus be retrieved with sufficient accuracy.

The above considerations apply both to the optical and the microwave instruments.

6.3.5. Operation Modes

The Earth Explorer Topography Mission would be designed for a maximum of autonomy. This implies a minimum number of instrument and satellite operation modes, which can be controlled by means of timelines stored in an onboard computer. Apart from the routine operations allowance needs to be made for instrument calibration to meet the mission performance requirements.

The definition of all operation modes depends on the design of the instruments and the platforms, which would evolve in the course of the Phase A study.

6.3.6. Lifetime

A minimum of 5 years has been specified for the duration of the observations. This can be achieved for the laser altimeter satellite without onboard orbit maintenance system. On the other hand, for the microwave altimeter satellite system concepts the onboard propulsion system would ensure orbit maintenance which is much more critical because of the lower orbit. The propellant supply must be sized accordingly.

6.4. Satellite Design

6.4.1. General Constraints

The design of the possible satellites is strongly affected by the choice of payload and orbit. Also the communication requirements play an important role in the definition of their configurations.

Reuse of existing design concepts has been considered to the extent possible to minimise the development effort. However, it is very unlikely that an existing platform could accommodate any of the payload options without significant modification because of the rather specific instrument configurations.

Satellite configuration concepts have been elaborated for all of the mission implementation options. They all differ considerably in resource requirements and complexity. It was not possible to arrive at the same level of maturity for all of these options in the framework of this report. More detailed work must be subject of a phase A study.

6.4.2. Ice Topography Explorer – Laser Altimeter Satellite System Concept

Configuration Concept

The most demanding configuration constraint arises from the characteristics of the orbit, which is not sun-synchronous. This results in a continuous change of right ascension and thus local solar time during a year. This change in local solar time covers a range from -180° to + 180° and thus a significant variation in solar aspect angle. The main impact on satellite configuration lies in the areas of thermal control (laser heat dissipation and alignment stability) and power generation (solar array). These problems could be alleviated by a strategy of turning the satellite around its yaw axis. The configuration concept of the Ice Topography Explorer is shown in Figure 6.1.

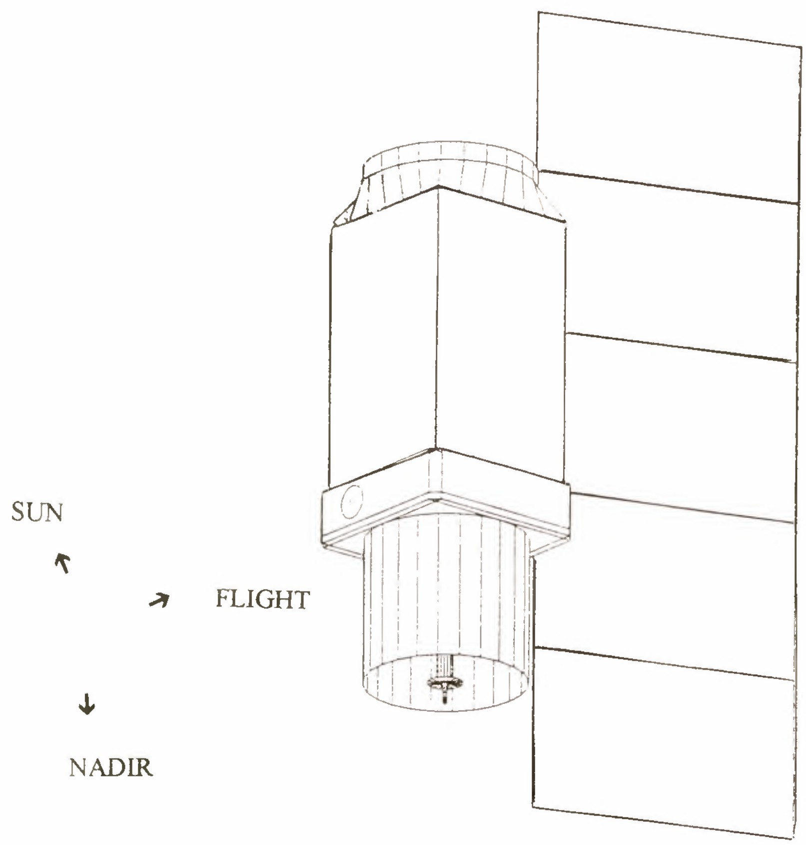


***Figure 6.1**. Ice Topography Explorer, Configuration Schematic*

Satellite Design Concept

The laser altimeter is mounted on top of the box shaped satellite body. The dimensions are about 0.9 m $\times$ 0.9 m for the launcher interface with an overall height of about 2.8 m. The S-band and GNSS receiver antennas are mounted on deployable booms to satisfy the viewing requirements and make maximum use of the launcher payload volume envelope. The solar array, canted at 17° relative to the satellite velocity axis, rotates about a single axis to optimise electrical output. It will be stowed along the satellite body during launch.

The design of the thermal control subsystem is critical in that the heat dissipation of the laser via its radiator must be ensured for all phases of the mission.

The altimeter performance requirements mandate attitude pointing knowledge in the order of a few arcseconds, which is only possible with a star camera. The pointing knowledge must also include instrument alignment errors. Pointing control does not need to be maintained to a level better than about 1.5 mrad, which is equivalent to displacement of the foot print of 1 km from nadir. This requirement is well within the performance envelope of momentum wheels and magnetorquers. No propulsion system is needed as the orbit does not have to be controlled.

The data handling subsystem is based on the use of the Agency's packet tele-command and telemetry standard. Science data are merged with housekeeping data into a single data stream and stored in a solid state mass memory (SSMM). Data management is performed by a central onboard computer.

A standard S-band subsystem can be used to meet the requirements of all tele-communication scenario. Independent transmitters and receivers could be used as the ranging function could be replaced by the GNSS receiver to provide orbit data.

The design of the solar array is driven by the rather large changes in solar aspect angle. An array area of roughly 7 m^2 is required for an end-of-life power output of 750 W, which includes battery charge. High efficiency GaAs solar cells have been assumed as baseline. The energy storage requirements are in the order of 1 kWh to limit battery depth-of-discharge to about 25 % to ensure a five year mission life. A range of possible configurations exist for either single or double batteries with suitable capacity and cells numbers. The resource budget estimates are shown in Table 6.4.

Item	Mass	Power
Payload	75 kg	230 W
Platform	335 kg	400 W
Margin	40 kg	120 W
Total	450 Kg	750 W

Table 6.4. *Resource Budget Estimates for the Ice Topography Explorer*

6.4.3. Ocean Topography Explorer–Pulse Limited Altimeter Satellite System Concept

Configuration Concept

A possible satellite configuration is mainly constrained by the interfaces with the launch vehicle in terms of mass and volume as well as the field of view of the altimeter and the supporting radiometer. The selection of a sun-synchronous dawn-dusk orbit results in a rather straightforward configuration both with respect to the design of the solar array and the thermal control.

The general configuration is shown in Figure 6.2. It features independent propulsion, service and payload modules, which allows for parallel design, manufacturing and integration, however at the expense of more complicated interfaces. Further optimisation is required for the payload accommodation.

Satellite Design

The structure consists of a central thrust tube interfacing with the launcher via the propulsion module. All equipments are mounted on panels, which form the satellite body. They are arranged as shear and lateral panels, with platforms as top and bottom of the structure. Mechanisms are provided for the solar array and the MWR, which will be deployed after launch.

A passive thermal control subsystem has been selected because of its inherently simple design. Equipment temperature requirements will be met by means of selecting appropriate surface treatment, insulation blankets, radiator areas and heaters.

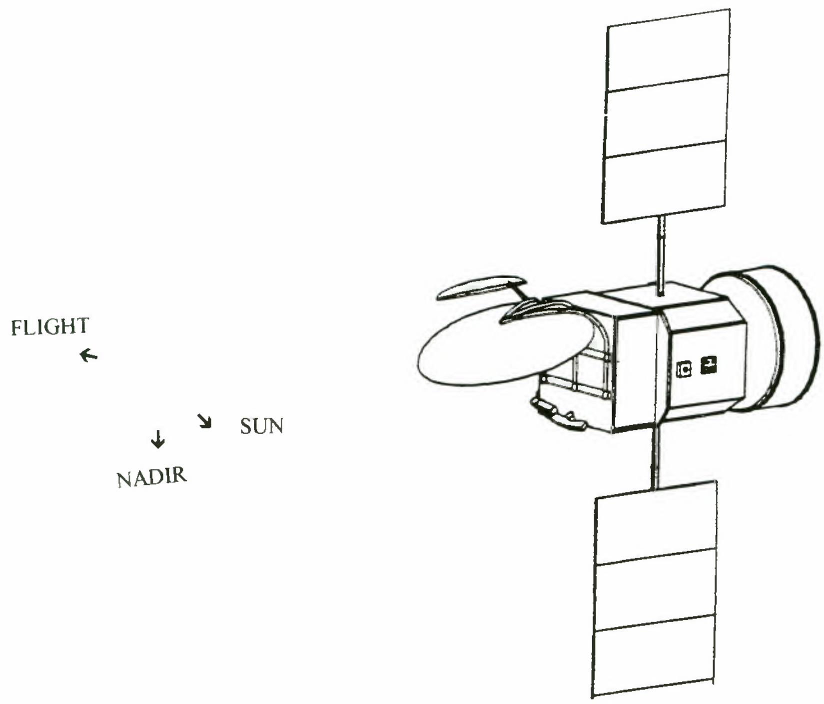


__Figure 6.2.__ Ocean Topography Explorer, Configuration Schematic

A preliminary assessment of the orbit control has shown that a delta V of roughly 250 m/s will be required for a five year mission. This can be readily achieved by means of a conventional hydrazine system with a fuel supply of 50 kg. Two independent thrusters are foreseen to implement redundancy and also allow for double thrust capability.

Earth pointing must be maintained to an accuracy of about 1.5 mrad in the roll and pitch axes to maintain instrument performance. This can be achieved by means of a control system using a set of momentum wheels controlled by Earth and Sun sensors, a magnetometer and a gyro package. The wheel capacity is 20 Nms and 0.04 Nm; they will be off-loaded by a magnetorquer with a momentum of 35 Am^2. Orbit determination is provided by the GNSS receiver which is also used for atmospheric profiling.

Data management will be controlled by a central computer, which could also perform the attitude control. Science and housekeeping data are collected in parallel, stored and formatted centrally for transmission to ground. Data storage has to be sized for the coverage of all blind orbits to avoid a loss of science data; about 4.5 Gb will be required.

Down linking of all data stored in the recorder is not feasible via an S-band link, even if spread out over several passes, as the required bandwidth is in the order of 3 Mbps. This can only be achieved by an X-band link.

The solar array consists of two wings stowed against the satellite side walls during launch and deployed in orbit. With the dawn/dusk orbit no solar array drive mechanism is required. An array area of about 3 m^2 is necessary if GaAs solar are used. The energy storage system comprises a single 24 cell 24 Ahr NiCd battery for the supply of eclipse loads.

The resource budget estimates are given in Table 6.5.

Item	Mass	Power
Payload	97 kg	107 W
Platform	245 kg	149 W
Margin	58 kg	44 W
Total	400 kg	300 W

Table 6.5. *Resource Budget Estimates for the Ocean Topography Explorer*

6.4.4. Combined Ice-Ocean Topography Explorer–High Resolution Altimeter Satellite System Concepts

This Section considers possible satellite concepts embarking the proposed high resolution microwave altimeter concepts described in Sections 6.2.4 and 6.2.5.

Beam Limited 94 GHz Altimeter Satellite System Concept

The configuration is determined by the radar altimeter antenna which has a diameter of 4.5 m. The S- and X-band antennas have been combined with the feed of the altimeter antenna, which is a possible configuration within the constraints of a small satellite and launcher. The altimeter antenna has to be stowed for launch to give a compact launch configuration. The accommodation of the microwave radiometer is still open. The configuration schematic of a possible 94 GHz Altimeter Satellite is depicted in Figure 6.3.

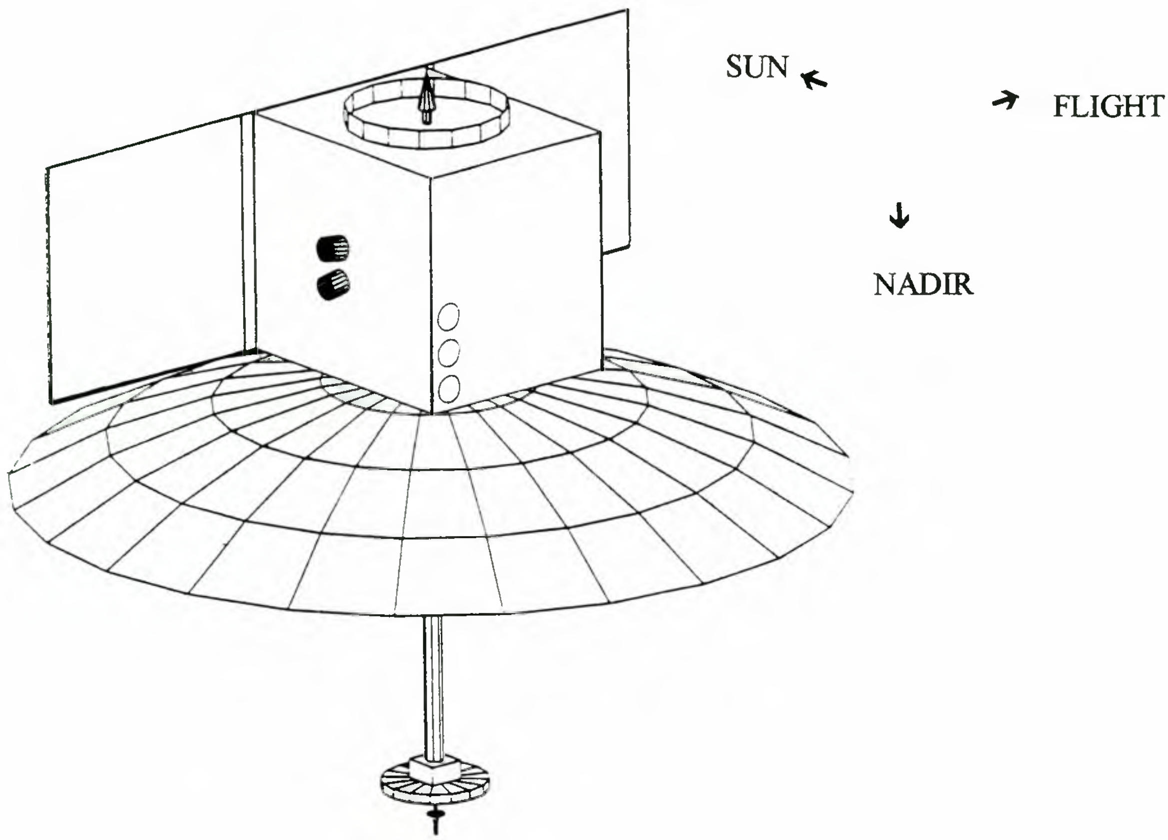


Figure 6.3. *Combined Ice-Ocean Topography Explorer, Configuration Schematic.*

The satellite structure consists of a box formed by panels and platforms with outer dimensions of about 1.5 m × 1.2 m × 1.3 m. The altimeter antenna is mounted on top of the structure opposite the launcher adapter. The solar panels deploy sideways in parallel with the flight vector. The design of the solar array and the thermal control is not critical because of the dawn/dusk orbit.

As discussed in chapter 4 ocean observations require the ground tracks to be repeated very accurately, which implies the use of an orbit control system. An ion propulsion system, such as considered for the Earth Explorer Gravity Field and Ocean Circulation Mission, could be a suitable baseline.

The high spatial resolution of the altimeter results in a requirement for attitude determination in the order of ten arcseconds, which can be only met by a star camera. Satellite pointing will be maintained by a set of momentum wheels and magnetorquers.

The instrument data, multiplexed with housekeeping data, are stored in a 75 Gb solid state mass memory. A central computer would manage the onboard data traffic.

The high data volume can be transmitted to ground by means of an X-band link. Housekeeping and tele-command use conventional S-band system.

The power requirements can be met by a solar array using GaAs cells with an area of approximately 6 m^2. The dawn-dusk orbit has only short eclipse periods resulting in a small energy storage requirement. A capacity of about 400 Whr is sufficient to cover the operational profile.

The resource budget estimates are shown in Table 6.6.

Item	Mass	Power
Payload	300 kg	185 W
Platform	565 kg	390 W
Margin	135 kg	75 W
Total	1000 kg	650 W

Table 6.6. *Combined Ice-Ocean Topography Explorer Resource Budget Estimates*

Interferometric Altimeter Satellite System Concept

Only a very preliminary conceptual satellite design is available at this stage. The general configuration is shown in Figure 6.4. One of the interferometer antennas and the MWR need to be stowed for launch.

Regarding the design of the satellite subsystems, similar requirements as for the previous concepts apply.

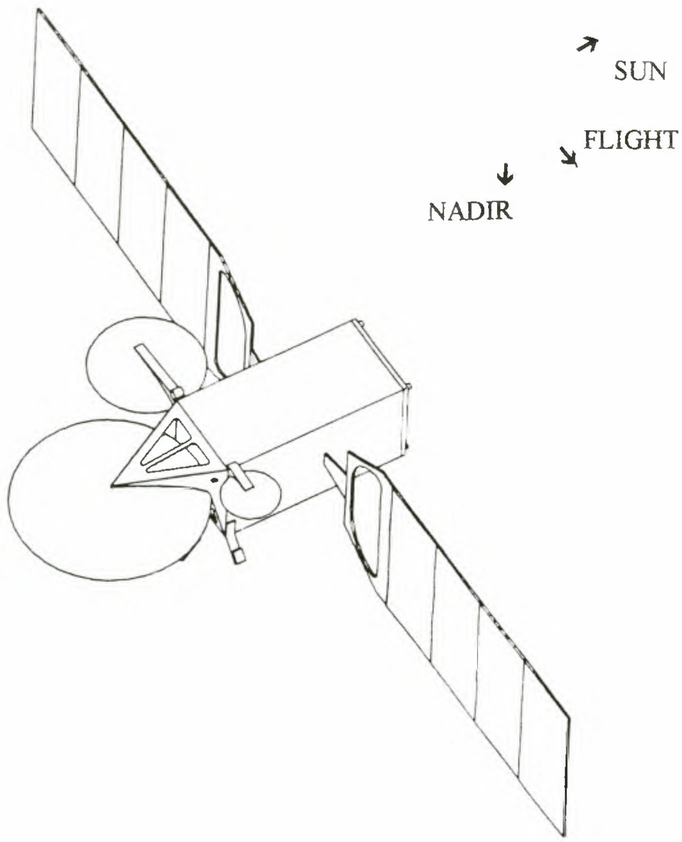


Figure 6.4. *Interferometric Altimeter Satellite System Concept, Configuration Schematic*

6.5. Launcher

All satellites concepts are compatible with a launch by the LLV2 or COSMOS vehicles. For the smaller concepts also EUROCKOT or TAURUS could be considered.

The possibility of launching any of these satellites as a passenger together with other missions is rather limited, because of the special orbit requirements.

6.6. Ground Segment

6.6.1 Overview

Figure 6.5 presents an overview of the ground segment. It includes four main elements, the Command and Data Acquisition Element (CDAE), the Mission and Satellite Control Element (MSCE), the Processing and Archive Element (PAE) and the Science Data Centre (SDC). Their functions are summarised below. There is confidence that the infrastructure expected to be in place in the year 2003 will be suitable with small adaptations for the support of the Earth Explorer Topography Mission in addition to other ongoing missions.

The following processing levels are identified:

- Level 0: raw data, time ordered and without overlaps;
- Level 1a: data depacketised, calibrations and geometric corrections computed and appended, but not applied;
- Level 1b: data with calibration and geometric corrections applied and geolocalised;
- Level 2: geophysical data.

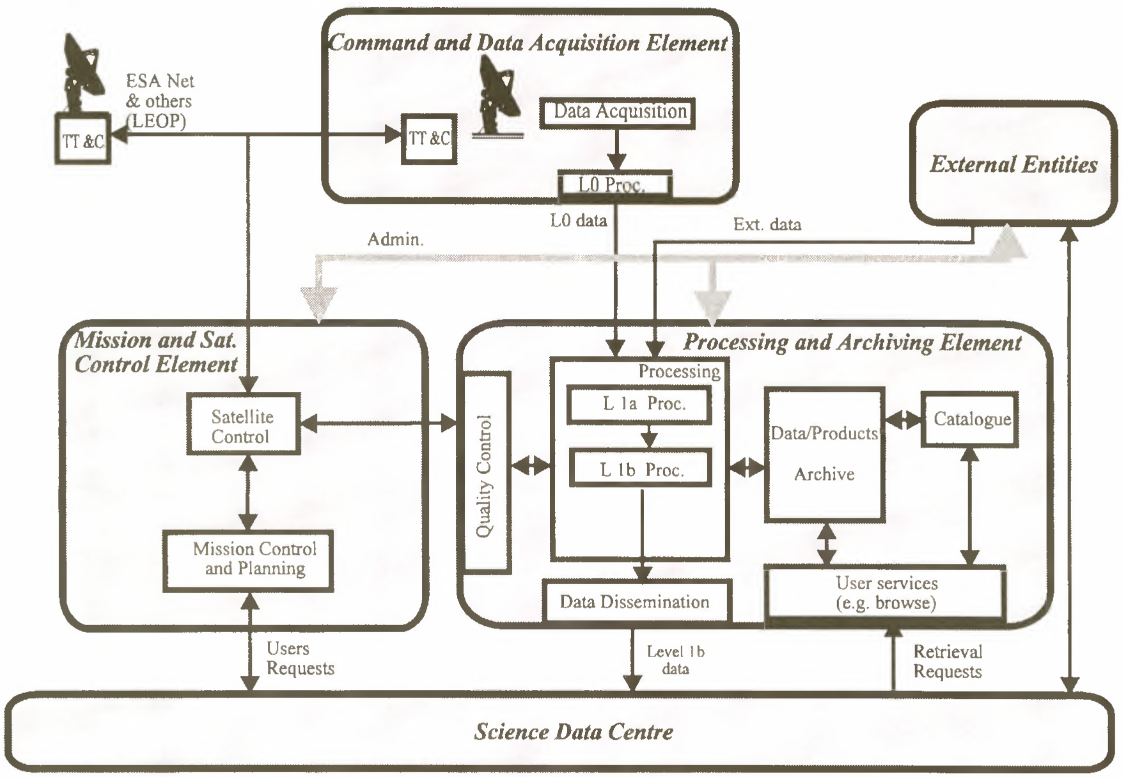


Figure 6.5. Topography Mission Ground Segment Concept

6.6.2. Command and Data Acquisition

The requirements on the CDAE will depend on the option selected for the space segment. A single European ground station, e.g. Kiruna would be sufficient to perform data acquisition and satellite command including the support of a two-satellite mission. The data would be processed to Level 0 by the CDAE, where they would be archived for a short time, e.g. one week.

6.6.3. Mission and Satellite Control

The MSCE would be responsible for the monitoring and control of the ground and space segments. The communication requirements between the elements of the ground segment are well within the capabilities developed for ERS and ENVISAT. Interaction between spacecraft and ground segment would be minimised by providing a maximum of autonomy in the design of the space segments.

6.6.4. Processing and Archiving

The PAE would processes the data to Levels 1a and 1b, as well as provide archiving for a given time upon completion of the nominal five year mission. The data would then be forwarded to the SDC. A catalogue and browsing facility would be provided for online access. The PAE would also interface with external entities, like the International GPS Services for Geodynamics and maintain data emanating from related missions as ENVISAT, TPFO, EOS Laser ALT and others for consistent utilisation of data.

6.6.5. Data Processing

The SDC would generate the data products from Level 2 onwards as identified in chapter 4 of this report. Processing algorithms already exist for radar altimeter applications as developed for the ERS and other missions. Laser altimeter algorithms would be based on the work started for ATLID. However, the high resolution altimeter concepts would require new developments.

The data products derived from the Earth Explorer Topography Mission would improve the initialisation and parameterisation of climate models. In addition, they would significantly contribute to future operational ocean and sea ice modelling provided the data are available for assimilation within about three days.

7. Programmatics

7.1. General

The Earth Explorer Topography Mission would be implemented in the frame of an ESA Earth Explorer Programme of research missions if selected after phase A studies carried out within the Agency's Earth Observation Preparatory Programme.

7.2. Critical Areas and Open Issues

As identified in chapter 4, considerable tradeoff and study would need to be performed in phase A before a selection among the various altimeter options could be made. In the simplest case for ocean topography observations an advanced version of the ERS and ENVISAT series of altimeters could be launched on a small platform with a microwave radiometer, a position determination package and a laser retro reflector of the ERS/ENVISAT type to continue the symbiosis with the TOPEX/POSEIDON series. The instrumentation is available and the expected developments are directed towards lower resource demands and cost. Processing algorithms are available and the scientific community is well established.

For an ice topography explorer mission based on the laser altimeter, the instrument would be a new development. However, experience has been accumulated in the frame of more complex developments such as ATLID and ALADIN. As the payload requirements on the platform are modest, no critical problems are identified at platform level. The critical concern is the mission return from a laser system observing areas of high cloud coverage.

High resolution microwave options would avoid the cloud cover problem but concepts to provide the required spatial resolution are not yet as mature.

7.3. Related Missions and Timeliness

Related to the ocean element of the Earth Explorer Topography Mission are the ENVISAT and proposed TPFO and GFO missions. A launch around 2003 has been foreseen to provide continuity with the ENVISAT altimeter mission. An earlier launch should however be recommended if tandem observations are required.

Related to the ice topography explorer satellite is the proposed US EOS Laser ALT mission which has similar objectives. If the laser altimeter option is selected for the Earth Explorer Topography Mission then a combination with the EOS Laser ALT could offer useful complementarity. This combination, which could offer operations of two lasers missions partly in parallel and partly in series, would provide a longer timeseries of laser altimeter data with a denser sampling. This is very advantageous given the cloud coverage in the polar regions (see section 4.6).

If a high resolution microwave option is selected, the above arguments for coordination with ENVISAT are again applicable, as this option would also provide ocean topography observations. The timeliness for coordination with ENVISAT is further strengthened by the potential enhancements that could be achieved by planning the Earth Explorer Topography Mission observations with the ENVISAT ASAR observations. The latter would provide ice velocity and thus the tandem would be a unique opportunity to obtain direct ice flux estimates. A part of the mission should also preferably fly jointly with the EOS Laser ALT to provide cross-overs between the laser and the high resolution microwave observations.

7.4. International Cooperation

Ocean and ice topography observation requirements cannot be satisfied with uncoordinated missions by individual Agencies. The Earth Explorer Topography Mission has therefore to be seen in an international context that includes related missions such as TPFO and EOS Laser ALT. This context could be the frame to establish international cooperation. The implementation of such cooperation would have to be discussed in parallel to the phase A.

7.5. Enhancement of European Capabilities and Applications Potential

The research areas identified in chapter 2 have clear application potential. Both ocean and ice altimeter could be precursors for operational systems.

The development of beam limited laser altimeter or high resolution microwave altimeter would expand the European capabilities for topography observations.

The observation of inland waters and the provision for reference heights for interferometric studies will moreover have applications in areas of land topography and hydrology.

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List of Acronyms

AATSR	Advanced Along Track Scanning Radiometer
ACSYS	Arctic Climate System Study
ADEOS	(Japanese Satellite planned by NASDA; launch: 1996))
AITMP	Arctic sea Ice Thickness Monitoring Programme
AnITMP	Antarctic sea Ice Thickness Monitoring Programme
ALADIN	Atmospheric LAser Doppler INstrument
ALOS	Japanese Advanced Land Observing Satellite planned for 2002
AMSR	Advanced Microwave Scanning Radiometer (NASDA)
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced Scatterometer
ASTER	Advanced Thermal Emission and Reflection Radiometer
ATLID	ATmospheric LIDar
AVHRR	Advanced Very High Resolution Radiometer
AVNIR	Advanced Visible and Near-Infrared Radiometer
CDAE	Command and Data Acquisition Element
CFRP	Carbon Fibre Reinforced Plastic
CLIVAR	CLImate VARiability and predictability (WCRP)
CME	Computing Modelling Effort
CNES	Centre National d'Etudes Spatiales (France)
CEOS-WGD	Committee on Earth Observation Satellites – Working Group Data
DCW	Digital Chart of the World
DEM	Digital Elevation Model
DMA	Defense Mapping Agency
DTED	Digital Terrain Elevation Data
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño/Southern Oscillation
EOS	Earth Observing System
ETM	Enhanced Thematic Mapper
ENVIRONMENT	(A European Union science and technology Programme)
ENVISAT	ENVIronment SATellite developed by ESA (launch: 1999)
EOS Laser ALT	Laser altimeter mission under NASA's MTPE (launch: 2003)
ERS	European Remote Sensing satellite (ESA)
FRISP	Filchner Ronne Ice Shelf Programme
GCM	Global Climate Model
GCOS	Global Climate Observing System (WMO/ICSU/UNEP/IOC)
GFO	Geosat Follow-On
GIS	Geographic Information System

GLOBE	Global Land One kilometre Base Elevation (BAD GLOBE = Best Available Data; GOOD GLOBE = Globally Only Open access Data)
GLOCHANT	Global Change and the Antartic
GNSS	Global Navigation Satellite System
GOOS	Global Ocean Observing System
GRAS	GNSS Receiver for Atmsopheric Sounding
HRVIR	High Resolution Visible and Infrared Radiometer
ICSU	International Council of Scientific Unions
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IPCC	International Panel on Climate Change
IPAB	International Programme for Antarctic Buoys
ITASE	International Transect of Antartica Scientific Expedition
MOLA	Mars Orbiter Laser Altimeter
MOMS-2P	(German-Russian planned satellite)
MSCE	Mission Operations and Satellite Control Element
MTPE	Mission to Planet Earth (NASA Programme)
MWR	Microwave Radiometer
NCAR	National Center for Atmospheric Research (USA)
NGDC	National Geographic Data Center (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
NSCAT	NASA Scatterometer (to be flown on ADEOS in 1996)
NWP	Numerical Weather Prediction
OSSE	Observing System Simulation Experiment
PAE	Processing and Archieving Element
PDF	Probability Density Function
psu	practical salinity unit
RADARSAT	Canadian radar satellite
RA-2	Dual-frequency Radar Altimeter flown on ENVISAT
rms	root-mean-square
RISP	Ross Ice Shelf Programme
rss	root-sum-square
SAR	Synthetic Aperture Radar
SCAR	Scientific Committee for Antarctic Research
SDC	Science Data Centre
SMMR	Scanning Multifrequency Microwave Radiometer
SPOT	Satellite Probatoire de l'Observation de la Terre (French satellite series)
SRTM	Shuttle Radar Topography Mapper
SSM/I	Special Scanning Microwave Imager

SSMM	Solid state mass memory
SST	Sea Surface Temperature
Sv	Sverdrup (unit for mass transport in the ocean, i.e. 10^6 m^3 s^{-1})
TOGA	Tropical Ocean – Global Atmosphere (WCRP)
TOPEX/POSEIDON	A joint US/France altimetric mission (also T/P in text)
TPFO	TOPEX/POSEIDON Follow-On (NASA/CNES)
TMWG	Topography Mission Working Group
UNEP	United Nations Environment Programme
WCRP	World Climate Research Programme (WMO/ICSU/IOC)
WMO	World Meteorological Organisation
WOCE	World Ocean Circulation Experiment (WCRP)

European Space Agency
Agence spatiale européenne

Contact: ESA Publications Division
c/o ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands
Tel (31) 71 565 3400 - Fax (31) 71 565 5433