CryoSat: A Mission to the Ice Fields of Earth

The transport of Arctic sea ice east of the Greenland ice sheet captured in an Envisat MERIS image. Each year 2000 gigatons of sea ice is transported by the East Greenland current into the Greenland Sea, where, in melting, it moderates the salinity 'pumps' of the ocean conveyor

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The accurate prediction and observation of the ice masses at the poles, and particularly of their rates of change, is of interest to us all, not least because 5% of the Earth's population live just 1 metre above sea level. Native Arctic populations face profound changes to their way of life and even existence. Economic interests, associated with oil and gas and trans-Arctic shipping, will grow as the pack ice declines, as too may strategic concerns over the sovereignty of the Arctic Ocean. The loss of pack ice may also affect the circulation of the Atlantic, and with it the winter weather of Western Europe. CryoSat is ESA's first mission dedicated to the observation of the Earth's polar ice masses. Its goals are to determine if there is indeed a downward trend in the mass of Arctic sea ice, and whether we should regard Antarctica as under threat from global warming.

At the Melting Point

Viewed from space, the largest change in the appearance of the Earth over the next century will be the almost complete destruction of the Arctic polar cap. The ice covering the Arctic Ocean is a thin layer of frozen seawater, thickening each winter in the polar night, and thinning each summer in the Sun of the polar day. As atmospheric warming approaches the poles from lower latitudes, summer melting will expose the Arctic Ocean. Heat stored in the surface water will delay on the onset of freezing the following winter. Less ice will form and, year on year, the thickness and coverage of ice will decline until the Arctic Ocean takes on the blue of the ice-free oceans to the south.

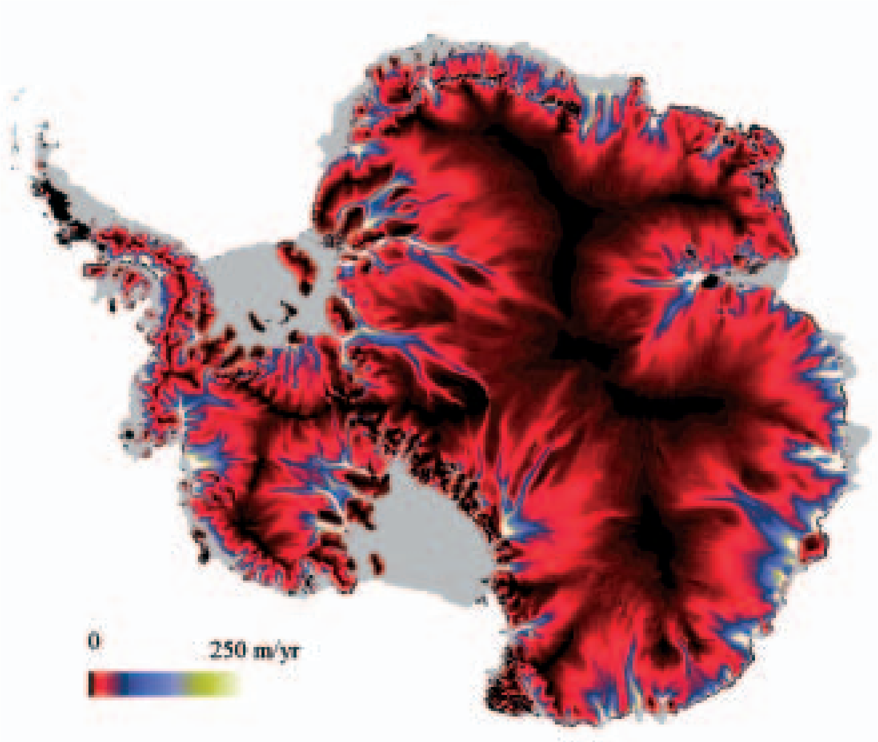
The floating shelf edge of the West Antarctic ice sheet. In the Pine Island Bay, warm ocean currents have made their way beneath the fringing, floating shelves to melt the ice sheet at great depth at its point of floatation. This has triggered a flow from the inland ice accounting for one fifth of present sea-level rise (Photo courtesy of British Antarctic Survey)

A little further south lies the Greenland ice sheet, the one surviving relict of the great ice sheets that covered North America and Eurasia some twenty thousand years ago. Although a survivor, it is only just clinging on. Only its own height protects it from the winds that circulate around its base, which are far warmer than those during the period of its growth. Even so, half of the snow falling on its high plateau is lost through melting each summer. A small temperature rise of a few degrees is all that is needed for all of the year's snowfall to be lost each summer. Once that point is reached, the ice sheet faces inexorable and accelerating decline. The lower it falls, the warmer its surface becomes. In perhaps a thousand years, its three million gigatons of ice will have become seven metres of global ocean, completing what the arrival of the interglacial climate ten thousand years ago was not quite able to achieve unaided.

At Earth's southern pole lies the Antarctic ice sheet. Its defences to the threat of warming at lower latitudes are far more formidable than those of Greenland. Its pure white surface offers little storage for heat from the summer Sun, and in winter temperatures drop to minus sixty centigrade in the intense cold of the polar night. The zonal winds of the Southern Hemisphere, unimpeded by continents, insulate the Antarctic atmosphere from events further north, and a succession of ocean fronts maintain ever colder water as the ice sheet approaches. Even so, its ramparts may be breached. Warm water, whose source lies far to the north in the Atlantic, circulates around the Antarctic continent at depth, one thousand metres below the surface. In the western, Amundsen Sea sector of the continent, this water has broken the cordon of coastal fronts and gained access to the continental shelf. There, melting the ice-sheet base one kilometre beneath the surface, it has triggered an ice discharge that accounts for one fifth of the present rise in global sea level. Even the deep freeze of the Antarctic may not, it seems, be immune to our modest effort to change the Earth's surface temperature.

While the demands of thermal equilibrium make the bleak long-term future of Arctic ice a fairly sure one, the same cannot be said of the rate at which its decline will occur. The machinery of numerical climate models is less secure in

A hot-water drilling site in Antarctica. This photograph gives an impression of the difficulties facing scientific explorers at the poles, even in favourable circumstances (Photo courtesy of British Antarctic Survey) predicting the consequences of atmospheric warming than the fact of it. This is true of many predictions – the thermal expansion of the ocean is a good example. It is particulary true of the Earth's ice masses, for which models must capture the mass balance between snowfall, freezing and melting, and the dynamic balance between the forces of gravity, flow and the stress of the wind and ocean currents. Today, numerical models neither capture the observed year-to-year variation of Arctic sea ice, nor the decadal growth and decline of the Antarctic ice sheet. Observation of actual change retains the essential role of experiment in policing the theory of numerical simulation, nowhere more so than of the polar climate.



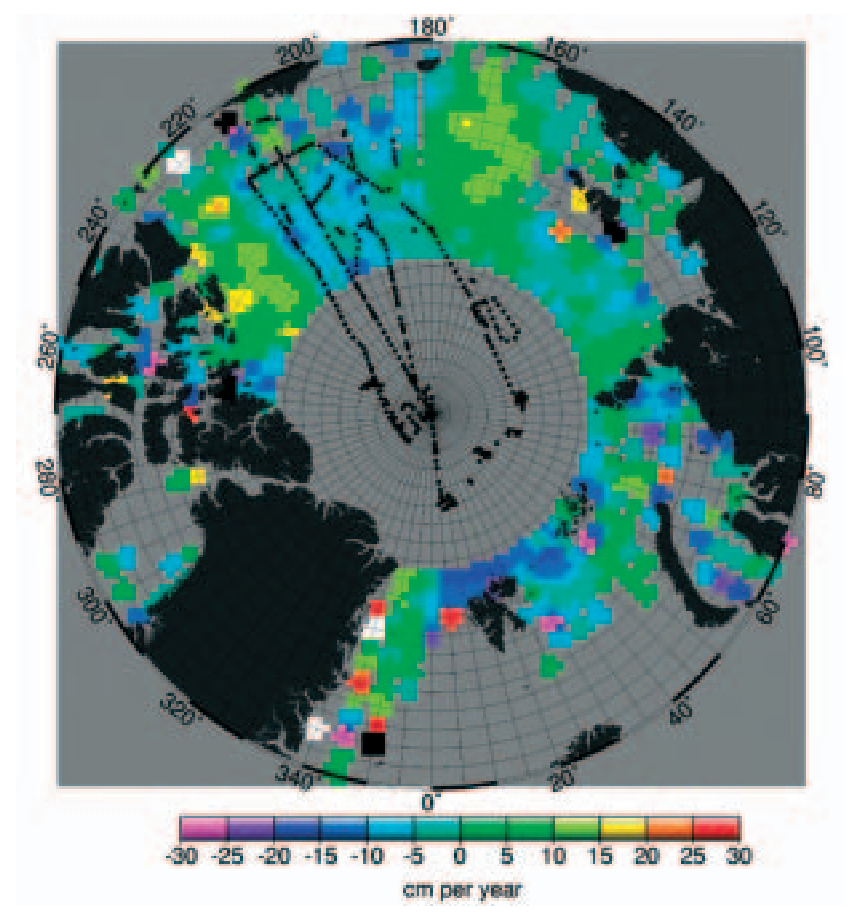
The ice streams of Antarctica. These frozen rivers of ice, up to 50 km wide and 3 km deep, extend deep into the Antarctic interior. They were the last great rivers of Earth to be accurately mapped, by this image derived from ERS-1 altimetry in 2000 (Copyright: Science, 2000)

Has the Thaw Started?

The first polar exploration dates from the early 20th century, and organised scientific exploration from the 1950s. Since then, some hundreds of scientists have returned each summer to survey the geology, physics, chemistry and biology of the poles. This is a considerable effort, underpinned by a logistics infrastructure that requires some 100 MEuro annually. It is, nonetheless, a thinly spread resource and the difficulties are impressive. The Arctic Ocean and Antarctic Ice Sheet are each the size of Western Europe. Sub-zero temperatures and violent storms are common at sea level. They are unpopulated, and dark for half the year. In both hemispheres, pack ice presents a difficult and sometimes dangerous obstacle to exploration. Given that the global scientific polar resource is roughly that of a single nation's effort in meteorology, one starts to appreciate why our knowledge of the poles towards the end of the 20th century was roughly that of Europe's knowledge of Africa towards the close of the 19th.

In consequence, understanding the poles has been an incremental process; each year's activity adding a small improvement to what went before. In addition, most measurements could only be interpreted by appealing to a 'mean' or 'climatology', that is, a time-invariant, state. This is not uncommon in the Earth sciences. When data is very sparse in space or time, the most conservative assumption in one of uniformity in the gaps. Where variability was encountered, in snowfall for example, the tendency was to average it away, to consign it to a very rapid variation that could be considered 'noise'. Working this way, there was by the 1980s a fairly good understanding of this 'mean' state: we knew the shape of the ice sheets and had a good idea of their depth; maps were available of the 'average' thickness of Arctic ice, and of the snowfall in both hemispheres. Numerical models, as is often the way, could match these mean states: the shape of the Antarctic and Greenland ice sheets could be reproduced with models that included simplified representations of ice flow and heat flux; and the distribution of Arctic sea ice was explainable by describing the ice as flowing like honey.

By the mid-1980s, however, the pressing questions did not concern the mean state. They concerned the first derivative. How were the ice masses changing, and why? From the first, climate models predicted accelerated change in the Arctic as a result of a reduction in summer albedo. Was this observable? Antarctica may be too cold to be much affected by a slight warming, but it contained the equivalent of seventy metres of global sea-level rise: how much was in contributing to sea-level rise anyway? What was apparent was that these questions were unanswerable with the measurements available at that time. As late as 1992 a review concluded that, for all that we could be sure, Antarctica might account for all the observed rise in 20th century sea level, or none of it. It was not just trends that were unavailable. Even in 1998, when I came to specify the CryoSat mission, I could find no information concerning the natural variability of Arctic ice mass, and, if one doesn't know the natural variability, one can hardly distinguish our own, unnatural contribution to a climate fluctuation.



Arctic sea-ice thinning 1993 to 1999. For the first time, ERS altimetry provided a synoptic view of ice-thickness changes in the Arctic Ocean. The observations reveal areas of growth and decay, showing changes of up to 1 m over the six-year period (Courtesy of Seymour Laxon, University College London).

The Contribution of the ERS Satellites

What has started to alter this state of ignorance is a very twentieth century method of exploration: Earth-orbiting satellites, and, in particular, the European ERS satellites. Hyperbolic claims for Earth-orbiting satellites are often made, but it is in fact difficult to exaggerate the impact that these satellites have had in recent years. The ERS satellites carried active microwave radars to polar latitudes for the first time. Accurate radar altimetry at latitudes greater than 72 deg became available, and the last great rivers of Earth – the ice streams of Antarctica – were mapped throughout their length for the first time.

Another technical advance underpinned the ERS missions. The 1980s saw an order-of-magnitude improvement in the accuracy of low-Earth orbits. Better knowledge of Earth's gravity field and the arrival of microwave tracking systems made orbits accurate to 5 cm routine by the mid-1990s and, by sufficient averaging of data, changes as small as 1 cm per year became detectable. For the first time, a measurement system was in place to make accurate measurements of changes in Antarctic ice mass. In just four years of the ERS mission, the uncertainty in Antarctica's contribution to sea level had been halved. Moreover, a picture started to emerge, becoming more focussed year-on-year, of the regional changes in Antarctic ice.

What has made these Antarctic observations especially powerful has been another innovation of the ERS satellites: satellite radar interferometry. An ice sheet is a balance between ice accumulating through snowfall and ice lost through flow to its margins. Changes due to snowfall may be ephemeral; they may thicken an ice sheet one decade and thin it the next. Changes due to flow, however, particularly if they are spatially extensive, have a longer-term significance. The two may be distinguished if the pattern of thinning can be correlated with the pattern of flow. In the event, just as ERS altimetry was providing Antarctic thinning, ERS SAR interferometry was providing the detailed pattern of flow. We now know that a steady draw-down of a sector of West Antarctica is providing one fifth of the present rise in global sea level.

The other great innovation of the ERS was the discovery, by my colleague Seymour Laxon, that its radar altimeter echoes were sensitive, if closely examined, to the difference in height – some 20 cm – between sea-ice floes and the ocean surrounding them. Since we know the density of the ice and the sea water with some accuracy, this measurement, with some help from Archimedes, provides the thickness and mass of the ice floes. The discovery provided synoptic maps of ice thickness of large sectors of the Arctic Ocean and, with time, its temporal variability. It became possible to investigate with confidence how the total mass of ice varied from year-to-year, and how, year-on-year, the action of the ocean and the winds redistributed ice around the Arctic. For the first time, the natural variability of Arctic ice could be securely examined.

What makes the polar results of the ERS missions all the more surprising is that they were obtained opportunistically. The inclination of the ERS orbit was a consequence of the Sun-synchronous design of the SPOT platform; the altimeter was based on a design dating from the 1970s whose original purpose was to measure the ocean geoid. (Envisat, which extends the climate records of the ERS missions, has the same orbit and essentially the same altimeter design.) Viewed with polar spectacles, the orbit and radar altimeter have signal weaknesses. In both hemispheres, the orbit leaves

	Sea ice **10^5 km^2 at 50°**	**Ice Sheets** **10^4 km^2 at 70°**	**Ice Sheets** **13.7 x 10^6 km^2**
Residual uncertainty	5.3 cm/yr	11 cm/yr	0.7 cm/yr
Measurement requirement	1.6 cm/yr	3.3 cm/yr	0.21 cm/yr
Predicted accuracy	1.2 cm/yr	3.3 cm/yr	0.12 cm/yr

Table 1. CryoSat performance and measurement accuracy for its nominal three-year mission duration

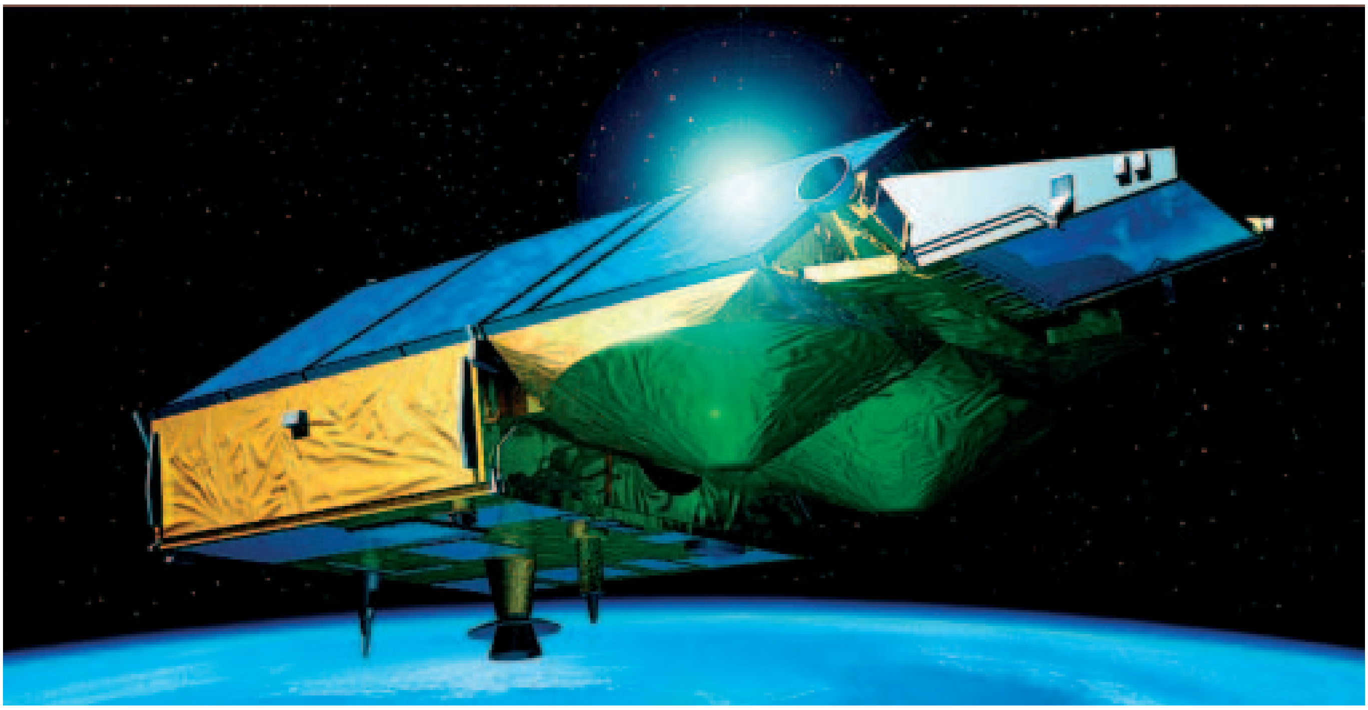
unsurveyed the 9 deg of latitude nearest the poles. The historical records of Arctic sea-ice thinning hint, at least, that the largest thinning falls in the missing sector. Moreover the region around North Pole marks the separation of Canadian- and Greenland-bound ice. To understanding the variability and the trend, the polar 'hole' needs filling. In the south, the 'hole' includes the southerly Ross Ice Shelf ice streams, which may, or may not be pursuing an on-going retreat from the last ice age.

The ERS and Envisat altimeters resolve only the largest of sea-ice floes; some 90% remain unsurveyed. The consequence of this is that the measurement density is low, and only by averaging over large space or time scales can usefully accurate measurements be made (typically, half of the observed Arctic). A great deal of the interaction of the ice with the wind and ocean is hidden from the measurements. The design also fails to deal with the marginal slopes of the ice sheets. This is more serious than it sounds: although comprising only 17% of the area, more than 35% of the snow falls in these marginal regions, and these are the regions most exposed to a warming atmosphere (in the Arctic) or ocean (in the Antarctic).

CryoSat – Starting with a Clean Sheet

CryoSat is ESA's first satellite that is dedicated to observing changes in the polar ice masses. It has two goals. Firstly, the mission seeks to build a detailed picture of the trends and natural variability in Arctic sea ice, and provide a dataset with which to examine the roles of the atmospheric and oceanic heat fluxes, and the winds and the ocean currents, in redistributing ice in the Arctic Ocean from year to year. Secondly, the mission seeks to completely observe the trend in thinning rate of the great ice sheets of Antarctica and Greenland.

How accurately must it do this? The performance of a satellite mission is simply the uncertainty that remains at the end of the mission. If one aims to measure a trend, one can never do this better than the limit allowed by natural variability. CryoSat has been designed to ensure that the residual uncertainty in ice trends is no more than 10% greater than the limit of natural variability; speaking more loosely, it has been designed so that the measurement error is a great deal smaller than the variations of the ice sheets



Artist's impression of CryoSat in orbit. The twin dishes of the interferometer are prominent in the foreground, with a star-tracker baffle apparent on the zenith face of the interferometer bench. The DORIS, X-band and S-band antennas are visible on the nadir panel, which is also the principal radiating face of the satellite. The triangular 'nose' is also a radiator. Body-mounted GaAs solar panels cover the zenith faces themselves. For the three years of the mission lifetime (a budgetary and not a scientific constraint), this leads to the mission requirements in Table 1.

Clearly, the scientific importance of CryoSat would be even greater if the mission were to be repeated. This said, the performances listed in Table 1 are sufficient to ensure that CryoSat, during its lifetime, will both allow us to determine whether the trends in sea-ice thickness reported from sparse historical submarine records reflect the onset of global warming or merely the ephemera of atmospheric variability, and reduce the uncertainty regarding the contribution of the Antarctic and Greenland ice sheets to sea level to that of other sources of ocean volume. In any case, CryoSat's performance is, more or less, as good as it may get: further improvements in measurement accuracy would have very little impact on the residual uncertainty.

This approach to specifying the mission requirements is very different from the past. Then, performance was an opportunist outcome. Here, we have started with a clean sheet. What new challenges result? As an oversimplified summary, the performances in Table 1 demand at the smaller spatial scales an improvement of three to ten times that of missions of the ERS and Envisat class. At the largest spatial scale, they also demand truly polar coverage. To meet these performances with an altimeter mission, one has at one's disposal, essentially, the accuracy of an individual measurement, the spatial sampling density, and the orbit inclination. In fact, the accuracy of an individual CryoSat measurement is similar to those of its predecessors; it is improving the sampling density that provides the order-of-magnitude improvement demanded by Table 1.

Sampling density is determined by the length of orbital track per unit area (or number of crossovers per unit area), the along-track sampling interval of the transmitted pulses (which cannot be greatly increased) and, crucially for an altimeter, the proportion of measurements successfully retrieved from the radar echoes. By selecting a retrograde orbit inclination of 92°, the orbit sampling at latitudes greater than 70° is greatly increased (by up to two orders of magnitude) over that of lower inclinations. Selecting a long repeat cycle (369 days) further improves on the orbit cross-over density of earlier missions (while maintaining a 30-day sub-cycle ensures monthly sampling of the moving sea ice). A 92° inclination does not quite provide complete coverage (some 5 x 10^5 km^2 of a total ice sheet area of 13.7 x 10^6 km^2 is lost), but pushing the inclination further polewards has a heavy penalty in terms of orbit sampling between latitudes of 70° and 80°.

As we have noted, for instruments of the ERS and Envisat class, the retrieval probability is less than 0.1 over sea ice, and close to 0 over the ice-sheet margins. The performances of Table 1 also demand a new class of instrument. The problem is essentially one of instrument resolution. Pulse-limited altimeters can resolve the freeboard of only the largest sea-ice floes, and the complex geometry of the ice margins makes their echoes too complicated to interpret. The CryoSat radar, 'SIRAL', meets this demand through two innovations. Firstly, the resolution is improved by a factor of 10 by the addition of synthetic-aperture processing in the along-track direction. By reducing the resolution to 1 km from 10 km, we expect to improve detection probability to some 70% of sea-ice floes. Secondly, by adding an additional antenna in the across-track direction, radar interferometry may be used to determine the direction of the echoes from the complex topography of the ice-sheet margins. We expect that this, together with the reduction in clutter provided by the synthetic processing, will raise the detection probability in the marginal regions to around 0.4. Taken together, the actual design of CryoSat's orbit and altimeter result in the predicted measurement accuracy given in the final row of Table 1, which meets, or is even slightly better than the required accuracy.

The Technical Challenge

Starting with a clean sheet is all very well, but one has to implement the consequences. Certainly there are significant technical demands compared with earlier radar-altimeter missions. The sampling demands of synthetic-aperture processing push the instrument into the high-bit-rate class – at 400 Gbit/day, the CryoSat data-rate is already 20% of that of the 13-sensor Envisat mission. The introduction of interferometry at 13.6 GHz places stringent demands on the mechanical stability of the interferometer baseline and on the phase stability of the radio-frequency (RF) and intermediate-frequency (IF) receivers, and on the internal calibration system. This is made more difficult by the range of solar illumination angles resulting from the orbit. The addition of interferometry also demands improvements in attitude knowledge: star-trackers must replace horizon sensors. There are other less-demanding but significant changes needed: upgrading of the radar power amplifier, for example.

Nonetheless, none of these demands were sufficient to question the practicality of the mission. The real practical challenge of CryoSat was its implementation within the target (1998) Opportunity Mission budget of 100 MEuro. That it has been possible at all is undoubtedly due to a number of historical factors. The first is the heritage of European industry. The Champ and Grace missions provided a high-inclination, non-Sun-synchronous, low-cost bus design that employed the Earth-facing panel as the principal radiator and used oversized, body-mounted solar panels to avoid deployables. The Topex/Poseidon and Jason missions also provided a heritage of high-performance radar-altimeter hardware that has, in the event, proved more than adequate to meet the new demands of interferometry. The second is the emergence (as an unexpected consequence of the Strategic Arms Limitation Talks) of inexpensive Russian launchers (in the case of CryoSat, based on the SS19 rockets). Thirdly, there has been the development of relatively inexpensive star-trackers based on CCD technology. Finally, the development of the Envisat ground stations at Kiruna and Svalbard, coupled with the arrival of inexpensive solid-state memory, will permit inexpensive operation using a single ground station.

In some respects too, the mission has been ruthlessly designed to cost. To maintain a single ground station approach, the use of the synthetic-aperture modes is limited (more or less) to the regions of sea ice and the margins of the ice sheet. Elsewhere, a conventional, low-bit-rate, pulse-limited mode is employed. The data acquisition, processing and distribution to users is carefully limited in its functionality. (This said, what spare capacity exists is now being employed to provide at least experimental use of the high-bit-rate modes over land and ice-free ocean surfaces, and a 'near-real-time' ocean wind and wave product is being implemented within the ground segment.) Perhaps more important is the recognition that a lower-cost mission demands an increase in risk; in particular, some elements of the radar will fly non-redundant.

There is one other factor that deserves comment. The low cost (and implicitly compressed schedule) of CryoSat has undoubtedly made higher-than-usual demands on the small Agency and industrial teams responsible for CryoSat. The level of this demand was perhaps not foreseen at the outset, but it has nonetheless been met across the board, and this too has been a major factor in meeting the constraints of a low-cost mission.

The Contribution of the CryoSat Mission

Without question, the most pressing question concerning the poles is whether our actions have already started an irretrievable process of climate change, and how fast this is happening. The measurements of CryoSat will not (any more than any other satellite) answer this question directly. For one thing, heat in the atmosphere and ocean is not separated into parcels, one of which is conveniently labelled 'anthropogenic contribution'. Ice mass, particularly sea-ice mass, is a sensitive measure of a warming atmosphere, but the problem of attribution remains. If one had a very good dynamic (that is, theoretical) description, it might perhaps be possible to identify the special character (the 'fingerprint') of an anthropogenically forced change, but it would be a brave act to claim that today for the polar ice bodies. The alternative is to have a good enough empirical record of the past situation that an anthropogenic change may be distinguished. It is in providing that empirical record of the natural variation that CryoSat will make its particular contribution.

CryoSat aims at measuring the ice mass budget. Like any fluid, this leaves open the momentum and energy budget. Here, however, the value of Cryosat measurements will be greatly increased by combining them with ice dynamics determined from SAR measurements, and in particular those of Envisat's global-monitoring mode. Taken together, the two data sets bear directly on two of the three conservation equations governing their flow. This is an approach that has already borne fruit in understanding Antarctic ice flow. For a very considerable time, the complexity of models of sea-ice flow has exceeded the capacity of measurements to criticise them. If scientists can grasp the nettle of combining these two data sets, new, more reliable predictions will result.

CryoSat is also a technical experiment. Its radar has not been flown before, and the mission has yet to prove that its payload may one day form the backbone of an operational system. In selecting a radar, Europe has taken a different path from the United States, which with Icesat attacked the resolution problem through laser altimetry. The selection of a particular technology is not an issue of principle, but of cost. In fact, there is reason to suppose that each technology has its advantages. The missions will overlap, however, and in observing the same ice will provide an opportunity to design an optimal 'operational' mission. It is worth reflecting that it has taken twenty years to perfect the ocean altimeter and to build modelling and assimilation tools with which to best use its observations. Seen against this background, there is every reason to expect that CryoSat will be a truly memorable mission.