The first of ESA's first Opportunity Missions: Cryosat

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The humans, animals and plants that populate the Arctic face an uncertain century. Rising surface temperatures mean all of us face change to some degree, but the Arctic faces a change in kind: the widespread disappearance in the next 80 years of the permanent layer of ice that covers the Arctic Ocean (Fig. 1). The permanent ice has characterised the Arctic since its earliest human occupation and by the standards of human habits at least the change will be profound. The change may not confine itself to the Arctic. Warm winter temperatures in Europe result from ocean currents that are affected by fresh water from precipitation and Arctic ice meltwater, and both these may increase in a warming climate. Europe itself may need to be concerned with the fate of the Arctic ice, for in this respect at least the polar tail may wag the mid-latitude dog.

Disappearing Arctic sea ice. The UK Hadley Centre HADCM2 model predicts a decrease in winter (March) ice thickness from ~5 m to ~1 m in the central Arctic for a 4 x CO_2 climate experiment.

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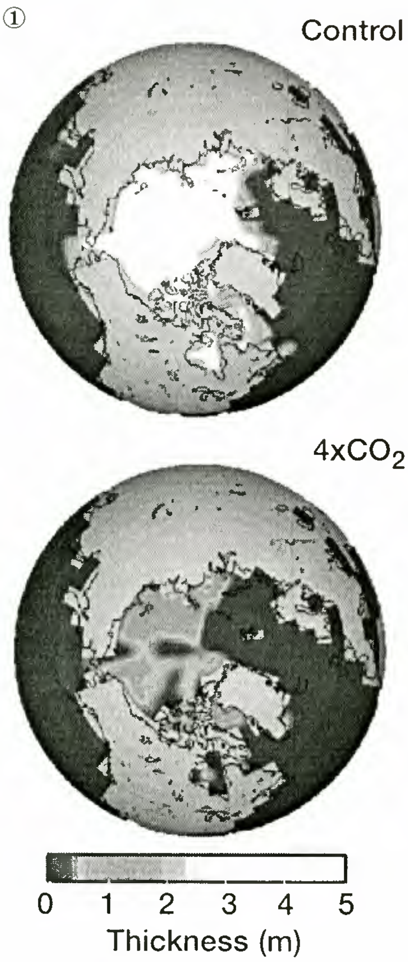

This is the scientific background that underpins the Cryosat mission, the European Space Agency's first Earth Explorer Opportunity Mission of its Living Planet Programme. The Cryosat mission was proposed by a team of scientists and engineers drawn from nine European countries, and selected from a field of 27 proposals. Cryosat aims to determine variations in the thickness of the Arctic sea ice and the ice sheet, ice caps and glaciers that ring the Arctic Ocean. For many years the difficulty of measuring sea ice thickness from space was regarded as almost insuperable, and yet it turns out that sea ice thickness may be even measured by the pulse-limited radar altimeters which have been flown for more than 20 years (Fig. 2).

ERS radar altimeter ice freeboard measurement. Echoes from large ice floes in the Fram Strait (77N) are distinguished from open water by their backscatter coefficient (upper panel). The residual elevation (i.e. elevation relative to an along-track mean of ocean elevation) shows a step between the ice and surrounding water. Variability in the open water is caused by the geoid and dynamic topography. Data gaps occur where echoes from a mixture of water and ice have been discarded by data-quality procedures.

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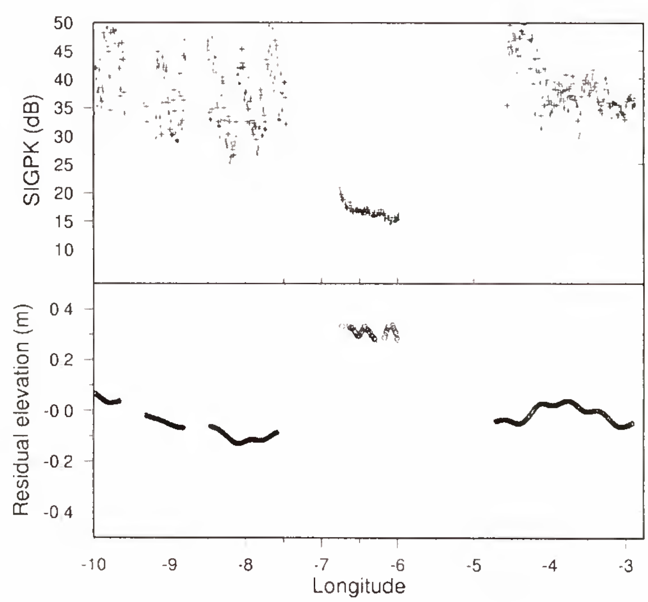

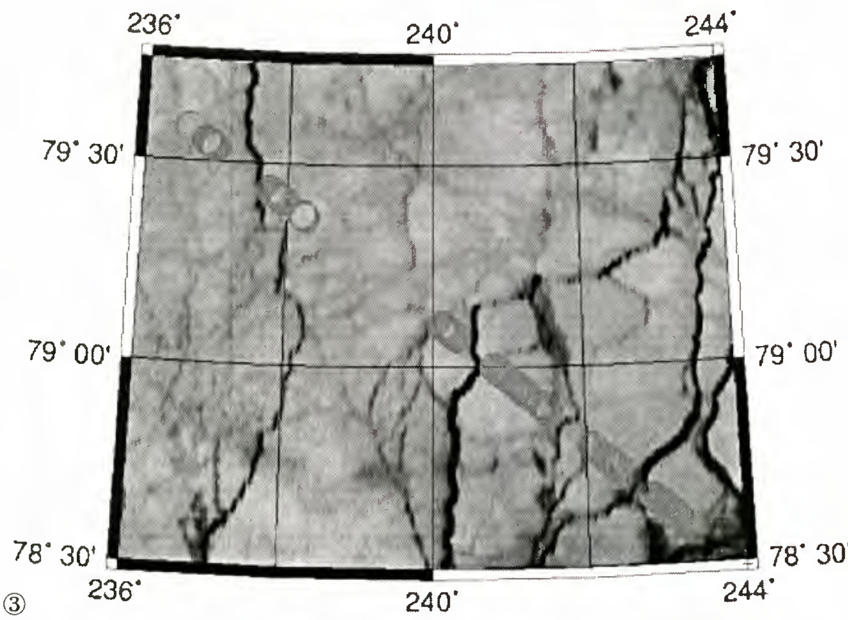

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ATSR imagery, north-west of Greenland, coincident with ERS altimetry, demonstrates that the low backscattering events over sea ice (indicated by circles whose diameter is that of the beam-limited footprint) correspond to large or consolidated ice floes. The restriction to very large floes limits the ERS measurement to around 5% of the total ice mass.

Cryosat altimeter operation. Left panel: Synthetic aperture processing is performed on an otherwise conventional Ku-band pulse-limited altimeter to form a set of high-resolution, along-track beams. As the altimeter progresses along its orbit, these beams sequentially scan each sub-satellite area. The data from all beams can be combined successively, leading to one height measurement for any given ground location. Right panel: Over ice sheets a second synthetic aperture system is added, as in (a), to form an interferometer across the satellite track. The angle of the echo at each range may be determined, and this, together with the range, determines the elevation and across-track location of the surface. When the across-track echo direction is unambigous, as in (i) or (iii), its coherence is high. Echoes at ranges in ambiguous directions, as in (ii), have low coherence, and may be masked.

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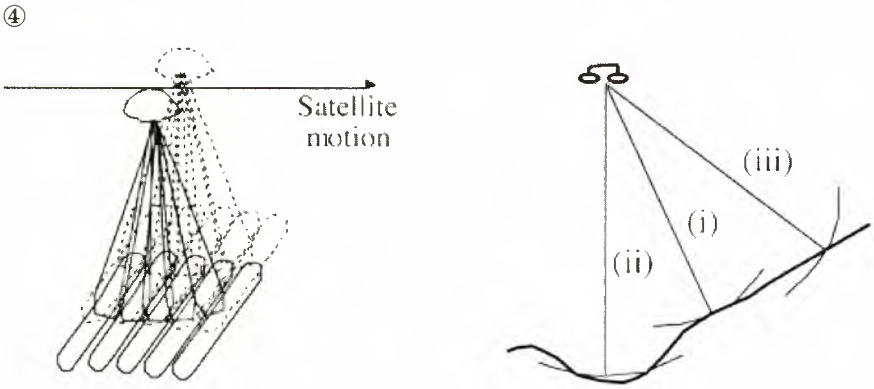
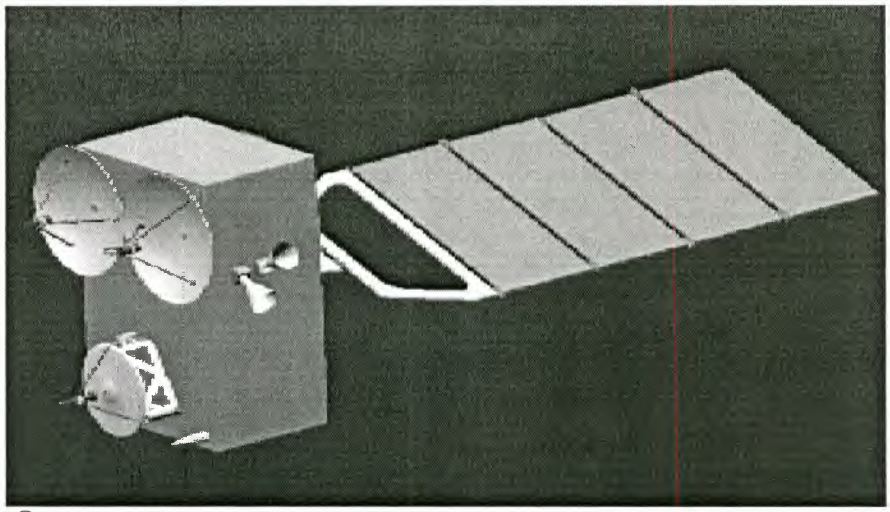


Unfortunately, only a small fraction of the ice may be observed this way (Fig. 3). The Cryosat mission team found a way of improving on this fraction - which meant improving upon pulse-limited altimeter resolution - while meeting the strict cost and time frames of the Opportunity Missions. The solution of the Cryosat team was to adapt existing European altimeter flight hardware with synthetic aperture and interferometric techniques (Fig. 4). This provided quite new capabilities, whilst (as it turned out) satisfying the Agency that the risk was manageable.

Sea ice thickness plays a central role in Arctic climate. Sea ice thickness determines the degree to which the winter Arctic atmosphere may benefit from heat stored in the ocean the previous summer. In the Arctic winter a heat flux of greater than 1.5 kW/m^2 is possible from the open ocean; the presence of ice may reduce this by one to two orders of magnitude. Second, sea ice mass fluctuations determine the fresh water forcing the ice provides to the ocean circulation. Presently, half of the freshwater flux into the Greenland Sea, some 2000 Gt/year, is provided by the wind-driven ice flux from the Arctic Ocean. Finally, sea ice thickness is very sensitive to ice thermodynamics and rheology (the way sea ice deforms under the action of stress), and the atmosphere and ocean heat fluxes. A heat flux of 10 W m^2 will melt around 1 m of ice in one year. Measurements of sea ice thickness provide a stringent test for climate models of polar latitudes.

It is possible that an irreversible change in Arctic sea ice mass is already underway. Existing ice thickness measurements may already signal an important trend in Arctic climate. But it is equally possible that the data merely reflect the ephemera of interannual variability at short spatial scales. Both views exist in the scientific literature. The difficulty faced by any would-be interpreter of these data is typical of polar climate data in general. The data are scattered too thinly in space and time to attach firm importance to variations they contain. Sea ice

thickness has previously been measured by drilling, by sonar observations of ice draft from submarines operating beneath the pack ice, or in one case from a moored sonar array across the Fram Strait. Measurements have accumulated over the years, but are rarely coincident in space. Thickness observed over short space scales is highly variable. It is extremely difficult to come to a conclusion as to the trends at the large scale. Cryosat, which aims to sample 70% of ice flows with spatial and temporal continuity, will provide a new and authoritative view of the fluctuations in Arctic sea ice.



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Artist's impression of Cryosat showing the two radar antenna dishes transmitting and receiving Ku-band radar echoes, the GPS patch antenna, a 5.5 m^2 GaAs solar array, 3 star-sensors and X and S-Band downlink antennas. (Figure courtesy of Dornier Satellitensysteme GmbH).

Cryosat will do more than observe the floating ice of the Arctic Ocean. Sea level has risen this century by 18 cm. An obvious source for this water is the solid ice accumulated on land in the form of ice sheets and glaciers. Observations from the European ERS altimeters, and the US Seasat and Geosat altimeters, seem to indicate that the great central plateaus of the Antarctic and Greenland ice sheets are stable. If these ice sheets are contributing to sea level, it appears that changes must be occuring in the marginal regions - the edges - of the ice sheets. On the other hand, extrapolations from the behaviour of some glaciers in other parts of the world have led to a view that it is the Earth's small ice bodies that are most at risk in a warming climate. The improvement in resolution of the Cryosat radar over that of its pulse-limited predecessors, coupled with its interferometric capability, will make spatially and temporally continuous measurements of the ice sheets margins and smaller ice caps possible for the first time. The second role of the Cryosat mission is to further our knowledge of the other wider role of the Earth's cryosphere: its effect on sea level.

Cryosat will determine trends in marine and land ice thickness over the duration of its nominal 3-year mission. Scientific interest in these trends spans a wide range of particular science; from, for example, the flow of individual glaciers to ice sheet mass exchange with the ocean as a whole. A problem for any satellite experiment designer is to map a range of science problems, which typically need rather different measurements, into a single experimental design. The approach the Cryosat team took was to prioritorise the science, and allow the most important science to determine the experiment design. This approach has its weakness - second priorities must take their chance with the measurements - but it does allow a thorough, quantitative approach to experiment design. The science requirements of Cryosat were stated as residual uncertainties (the uncertainties at the completion of the mission) in the trends in the thickness of Arctic perennial sea ice and Antarctic marginal ice sheet thickness. The measurement requirements were determined by requiring that the measurement error increased the residual uncertainty by no more than 10% of the natural variability. The requirements that arose are given in Table 1.

The final problem for the Cryosat team was to meet the very difficult envelopes of the Opportunity Missions: a total mission cost of 80 MECU, and a three year time to launch. The platform (Fig. 5) had to provide a non-sun-synchronous operation, but a free-drift orbit, and payload demand of ~ 50 W and 70 kg, was within existing European capability. The introduction of synthetic aperture and interferometric techniques transforms the capability of radar altimetry with existing European, flight-proven hardware. On the other hand, synthetic aperture operation

Table 1. The Cryosat Science and Measurement Requirements.

Requirement	Arctic Sea Ice 10^5 km^2	Ice Sheets 10^4 km^2	Ice Sheets 13.8×10^6 km^2
Science	3.5 cm/yr i.e.	8.3 cm/yr i.e.	0.76 cm/yr i.e.
Measurement	1.6 cm/yr	3.3 cm/yr	0.17 cm/yr

i.e. = ice equivalent.

Cryosat coverage is determined by the distribution of marine and land ice. Sea ice at its maximum extent covers the Arctic Ocean, Bering Strait, Kara Sea, Hudson Bay and Greenland and Norwegian Seas and extends in a down the east coast of North America to latitudes of 45°. In the Southern Hemisphere, the ice extends from the Antarctic continent to its maximum extent at 50° latitude. The land ice covers the Antarctic and Greenland Ice Sheets, the Russian, Norwegian, Canadian and Alaskan Arctic, and glaciers of the world widely scattered over the continents, including the Himalayas, the Rocky Mountains, Andes, European Alps and New Zealand Southern Alps. The red regions of the plot show where high resolution altimetry is required and green regions where pulse-limited is sufficient.

increases by a factor of 5000 or so the science data rate of the altimeter. The central question (as it turned out) was whether the data could be downlinked to a single ground station using an existing, ERS 105 Mbps link. The question was resolved by a combination of data storage on the platform, together with a careful appraisal (Fig. 6) of the coverage of the Earth demanded by the primary science goals.

Proposing the Cryosat mission depended on a rapid exchange of scientific demand and engineering constraint. In introducing into the Living Planet Programme missions selected through open scientific competition, ESA posed European Earth scientists a question it had not done previously. It replaced the simpler question of what science desires with the more difficult question of what science may be achieved within a fixed cost? The 27 proposals ESA received showed that European scientists had plenty of innovative answers to this question. But the competition is not simply a scientific challenge. It is a challenge to scientific compromise and to engineering practise. It requires a mission that may be implemented in 3 years from start to launch. This challenge now faces the Cryosat team. In making the Cryosat mission a success, European understanding of Arctic change, and European space industry, will be better equipped for the future.