

cryosat

→ ESA'S ICE MISSION

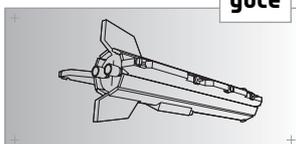


ESA'S EARTH EXPLORER MISSIONS

The Earth Explorer series of Earth observation missions focuses on the science and research elements of ESA's Living Planet Programme. Developed in direct response to issues identified by the scientific community, they aim to improve our understanding of how the Earth system works and the impact human activity is having on natural Earth processes. Earth Explorers are also designed to demonstrate breakthrough technology and remote sensing techniques and, together with the scientific questions addressed, form the basis for the development of new applications for Earth observation data.

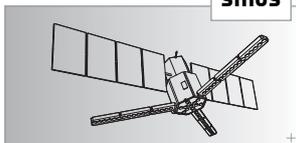
As a result of the continuing, user-driven approach for realising Earth Explorers, six missions have been selected so far for implementation:

goce



GOCE (Gravity field and steady-state Ocean Circulation Explorer) Launched in March 2009, GOCE is dedicated to measuring Earth's gravity field with unprecedented accuracy and spatial resolution. The resulting model of the geoid – the surface of equal gravitational potential defined by the gravity field – will advance our knowledge of ocean circulation, sea-level change and Earth-interior processes. GOCE will also make significant advances in geodesy and surveying.

smos



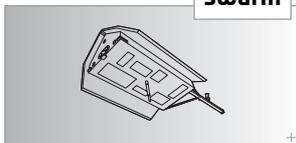
SMOS (Soil Moisture and Ocean Salinity) Launched in November 2009, SMOS is making global observations of soil moisture over landmasses and salinity over the oceans. The data will result in a better understanding of the water cycle and, in particular, the exchange processes between Earth's surfaces and the atmosphere. Data from SMOS will help to improve weather and climate models, and also have practical applications in areas such as agriculture and water resource management.

cryosat



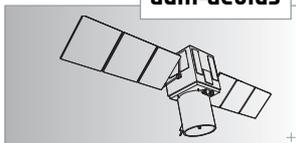
CRYOSAT The first mission to be selected, CryoSat will determine variations in the thickness of floating sea-ice so that seasonal and interannual variations can be detected. The satellite will also survey the surface of continental ice sheets to detect small elevation changes. Information on precise variations in ice thickness will further our understanding of the relationship between ice and climate change. The CryoSat-2 satellite replaces the original CryoSat, which was lost due to a launch failure in October 2005.

swarm



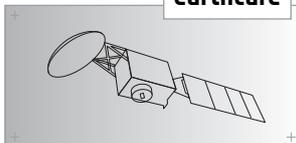
SWARM Swarm is a constellation of three satellites to provide high-precision and high-resolution measurements of the strength and direction of Earth's magnetic field. The models of the geomagnetic field resulting from the mission will provide new insights into Earth's interior, further our understanding of atmospheric processes related to climate and weather, and will have practical applications in areas such as space weather and radiation hazards.

adm-aeolus



ADM-AEOLUS (Atmospheric Dynamics Mission) Aeolus will be the first space mission to measure wind profiles on a global scale. The mission will improve the accuracy of numerical weather forecasting and advance our understanding of atmospheric dynamics and processes relevant to climate variability.

earthcare



EARTHCARE (Earth, Clouds, Aerosols and Radiation Explorer) EarthCARE is being implemented in cooperation with the Japan Aerospace Exploration Agency. The mission addresses the need for a better understanding of the interactions between clouds and the radiative and aerosol processes that play a role in climate regulation.

Further information about ESA's Earth Explorer missions can be obtained via:
www.esa.int/livingplanet



CRYOSAT: ESA'S ICE MISSION

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The marginal ice zone off the east coast of Greenland. Such zones form at the boundary between open and frozen oceans. The image was acquired by Envisat's Medium Resolution Imaging Spectrometer on 14 June 2008.

→ CRYOSAT

ESA's ice mission



ESA's Earth Explorer CryoSat mission is dedicated to precise monitoring of the changes in the thickness of marine ice floating in the polar oceans and variations in the thickness of the vast ice sheets that overlie Greenland and Antarctica.

With the effects of a changing climate fast becoming apparent, particularly in the polar regions, it is increasingly important to understand exactly how Earth's ice fields are responding. Diminishing ice cover is frequently cited as an early casualty of global warming and since ice, in turn, plays an important role regulating climate and sea level, the consequences of change are far reaching.

For some years now, satellites such as ESA's Envisat have been mapping the extent of ice cover. As stated in the *Climate Change 2007 Synthesis Report* by the Intergovernmental Panel on Climate Change, "Satellite data since 1978 show that annual average Arctic sea-ice extent has shrunk by 2.7% per decade." However, this is only part of the picture.

In order to understand fully how climate change is affecting these remote but sensitive regions, there remains an urgent need to determine exactly how the thickness of the ice, both on land and floating in the sea, is changing. By addressing this challenge, the data delivered by the CryoSat mission will complete the picture and lead to a better understanding of the role that ice plays in the Earth system.

The CryoSat-2 satellite replaces the original CryoSat, which was lost owing to a launch failure in October 2005. Following the loss, the mission was judged to be even more important than when it was first selected for development, and the decision to rebuild was taken. Almost exactly four years to the day after that decision, the new CryoSat-2, with a number of improvements, was ready for launch.

CryoSat's original objective was to determine if there was a trend towards diminishing ice cover. There now seems little doubt that there are indeed trends – the challenge now is to characterise them.

A synthetic aperture radar (SAR) image of the Arctic region. The image shows a complex landscape of ice and land. On the left, there is a large, light-colored area representing the Greenland Ice Sheet. To the right, the rugged terrain of Ellesmere Island is visible. A prominent, dark, winding feature in the lower center represents the Petermann glacier, which is the northern hemisphere's longest floating glacier. The image is composed of various shades of blue and white, highlighting the textures and structures of the ice and land.

Radar image showing the tip of Ellesmere Island (left) in the Canadian Arctic and northwestern Greenland (right). The light area to the left is the Greenland Ice Sheet, while the darker stream extending across the lower centre of the image is the northern hemisphere's longest floating glacier, Petermann. The image was made from Envisat Advanced Synthetic Aperture Radar data acquired in 2008.

→ ICE, CLIMATE AND SEA LEVEL

Ice plays an important role in regulating Earth's climate in a number of ways.

As solar radiation reaches Earth's atmosphere and surface, a certain percentage is reflected back out to space, depending on the 'albedo' (the reflectivity or whiteness) of the surface. Snow-covered ice has a high albedo and reflects about 80% of sunlight. Thus, once formed, ice tends to be maintained. As ice cover begins to melt, the albedo decreases and the combined effect of diminishing ice extent results in less solar radiation being reflected from Earth's surface. The surface then absorbs more and more energy, leading to positive feedback and resulting warming.

The polar oceans each year experience the formation and then melting of vast amounts of sea ice. At the North Pole, an area the size of Europe melts every summer and then freezes again the following winter. The thickness of this sea ice plays a central role in polar climate because it moderates heat transport by insulating the relatively warm ocean from the cold polar atmosphere.

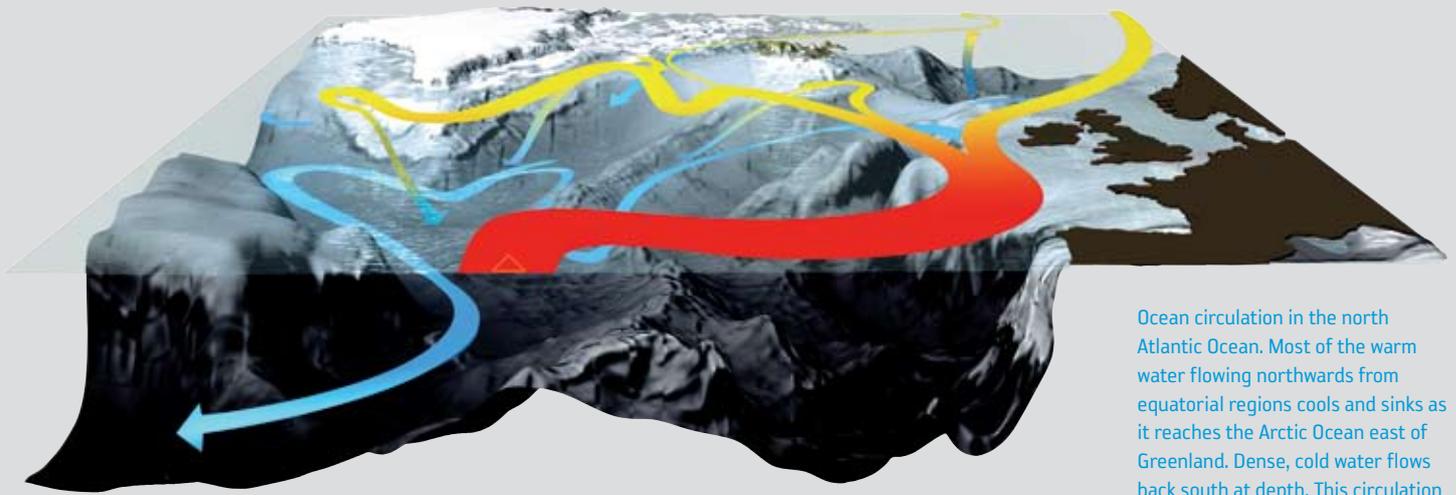
In addition, the seasonal changes of sea ice have a significant influence on the global ocean circulation pattern known as the 'thermohaline circulation'. As ice melts, there is an influx of fresh water into the surrounding ocean. This reduces the salinity and, consequently, the density of the water. Conversely, as the seawater cools and sea ice forms, the salinity and density of the surface seawater increase. This density increase causes the surface waters to sink and effectively to act as a pump, driving deep ocean currents towards the equator and away from the polar regions. To compensate for this loss, a return flow of warmer, less dense surface water is drawn northwards from low to high latitudes.

The Gulf Stream, which carries warm surface water northwards from the Gulf of Mexico to the sub-polar ocean east of Greenland, is extremely important for moderating the climate in Europe. The coastal waters of Europe are 4°C warmer than waters at the equivalent latitude in the North Pacific. These warm waters mix with surrounding water, and cool and sink as they reach the Arctic. If this circulation pattern were disturbed by reduced sea ice in the Arctic, there could be a profound effect on the strength and direction of this current. Clearly, an improved understanding of the fluxes of Arctic sea ice is important for predicting Europe's climate.

Lastly, the large ice sheets overlying land have an important effect on sea level. The Antarctic and Greenland ice sheets amount to about 28 million km³, which equates to sea level being 65 m lower than it would be if this ice were to melt. Until relatively recently, it was thought that these huge thick ice sheets were largely stable. However, recent observations have shown that regional changes are occurring much faster than previously expected.

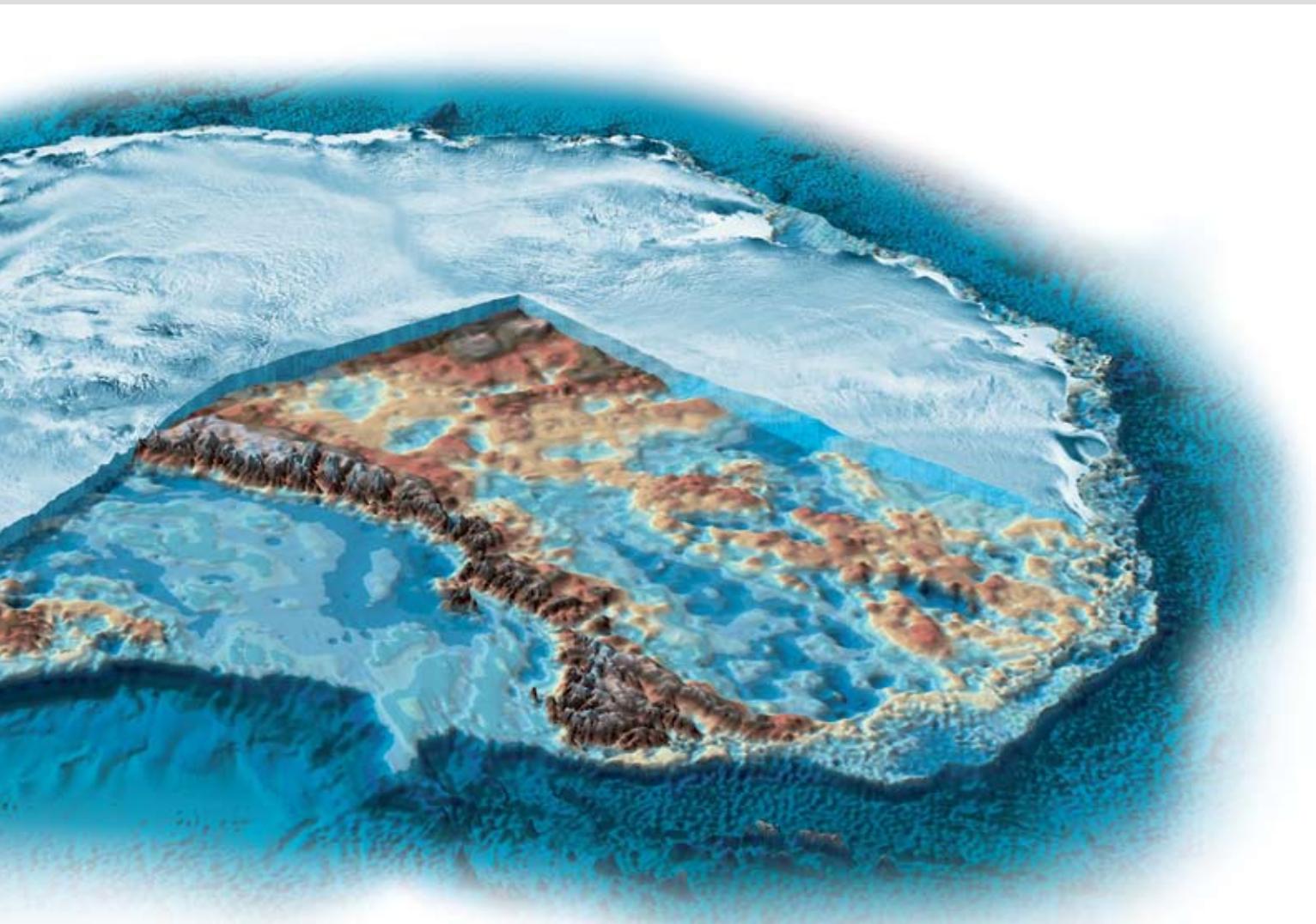


On average, the Antarctic ice sheet is more than 2 km thick and at its thickest it exceeds 4.5 km. Concealed under this dome of ice lie islands, mountains, valleys and lakes. As the image shows in blue shades, parts of Antarctica are below sea level, depressed by the weight of the ice. (National Geographic Maps 2002)

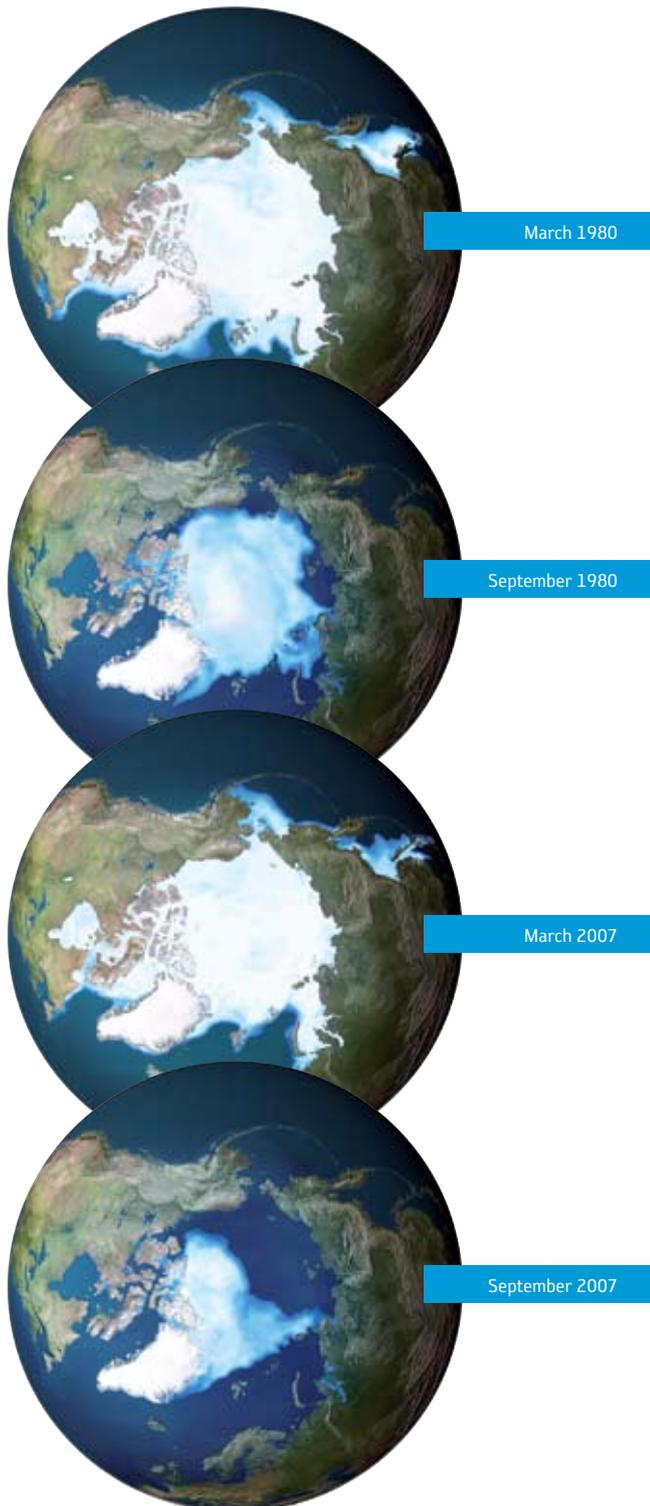


Warm surface circulation Cold intermediate and deep circulation

Ocean circulation in the north Atlantic Ocean. Most of the warm water flowing northwards from equatorial regions cools and sinks as it reaches the Arctic Ocean east of Greenland. Dense, cold water flows back south at depth. This circulation pattern is influenced by the sea ice that drifts from the central Arctic. Although the amount of sea ice varies with the season, it has a stabilising effect on ocean currents. A major decrease in sea ice could have a significant effect on this balance.



→ HOW IS EARTH'S ICE CHANGING?



There is now little doubt that the temperature on Earth is rising due to increased concentrations of greenhouse gases in the atmosphere. During the course of the last century, the average global surface temperature rose by about 0.6°C and 10 of the warmest years on record have occurred since 1997. Scientists are predicting that average global temperatures will rise by 4°C by the end of the century.

How rising temperatures will affect Earth's ice is still a hotly debated issue. However, recent evidence strongly suggests that ice cover is diminishing. One of the most dramatic signs of climate change has been seen in the extent of Arctic sea ice. Since 2000, the area of the Arctic Ocean covered by ice in the summer has reduced drastically, with the minimum occurring in September 2007. 2008 would have been a new record if it had not been for 2007, and 2009 was similar.

There is also emerging evidence of changes to continental ice cover. Before 2000, indications were that Earth's two major ice caps, covering Antarctica and Greenland, were generally stable, at least in their interiors. However, it is now known that the ice caps are melting at their base, caused by warming oceans. It has been discovered that a large glacial basin at the coastal boundary of West Antarctica – the Pine Island Glacier – is thinning at a rate of 16 m per year, acting as a huge drainage basin. Satellites also continue to observe the break up of the Wilkins Ice Shelf on the southwest side of the Antarctic Peninsula. In April 2009, rifts that had developed on the ice shelf led to the collapse of the ice bridge that connected it to Charcot Island.

Arctic ice cover for winter maximum and summer minimum for 1980 and 2007. While there is clear difference between the sea-ice extent at the end of the winter between 1980 and 2007, the summer minima show startling differences. In September 2007 the area covered by perennial sea ice shrunk to the smallest recorded since satellite measurements began 30 years ago.

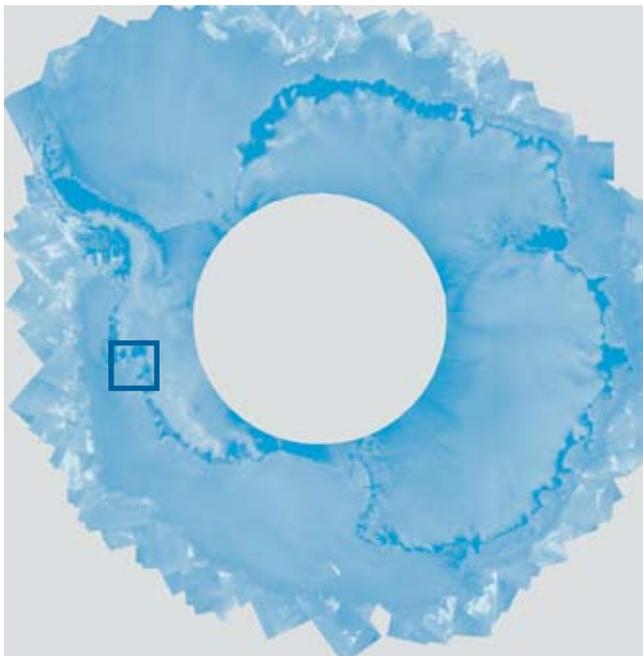
Melt water flowing into a large 'moulin' in the Greenland ice sheet. (R. Braithwaite)



New information about changes in continental ice cover has led to a projection of sea-level rise on the order of 1.4 m by 2100. This figure, cited in the 2009 report by the Scientific Committee on Antarctic Research *Antarctic Climate Change and the Environment*, is significantly higher than the 28–43 cm projections by the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (2007).

While there seems to be clear evidence that Earth's ice is changing, the real question is by how much. Reductions in the area of sea ice are readily observable using a variety of satellite remote-sensing techniques; however, there is only one practical way of converting this knowledge of 'area' of sea ice into 'volume' of sea ice. To do this conversion, information about ice thickness is needed – which is what CryoSat will measure.

CryoSat has been developed to measure thickness change not only in sea ice but also in the ice sheets on land. In particular, CryoSat carries sophisticated technologies to measure precisely changes at the margins of these ice sheets, where other satellite altimeter technology is currently limited. By accurately measuring thickness change in both types of ice, CryoSat will provide clear information to build a more detailed picture of exactly how Earth's ice is behaving.



Pine Island Glacier in West Antarctica is thinning so quickly that it could disappear within 100 years, potentially raising global sea level by around 25 cm. Research led by Prof. Duncan Wingham from University College London, UK, suggests that the central 'trunk' of the glacier lost four times as much ice in 2006 than it did in 1995 and is thinning at an accelerating rate. Pine Island Glacier moves more ice into the sea than any other Antarctic glacier, and is the fastest moving in the entire continent. (J. Yungel/NASA)

Envisat Advanced Synthetic Aperture Radar (ASAR) mosaic of multiple images, showing the location of the Pine Island and Thwaites Glacier regions. Central Antarctica is not imaged by ASAR owing to the limit of Envisat's orbit and its viewing geometry.

→ HOW CRYOSAT WILL DETECT CHANGE

The challenge

Fundamentally, there are two types of polar ice: ice that covers land and ice that floats in the oceans. Not only do these two forms of ice have different consequences for our planet and climate, but they also pose different challenges when trying to measure their thickness.

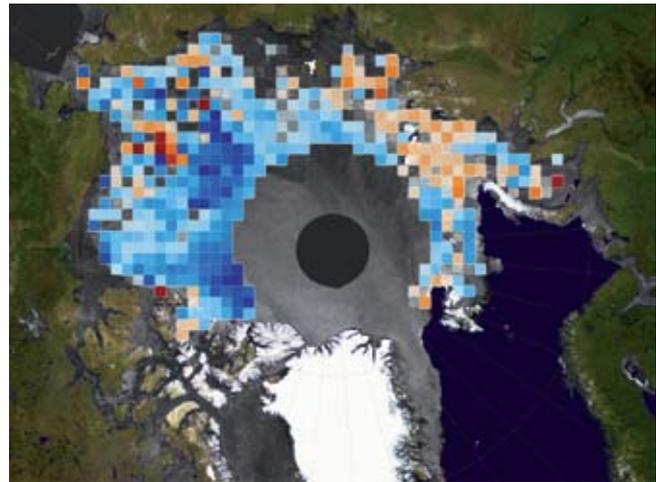
There is a strong link between Arctic sea ice and climate; changes in ocean circulation patterns and weather are associated with changes in sea-ice cover. Melting of this ice has no direct effect on sea level, because it is already floating. Since sea ice is relatively thin – just a few metres – its thickness can be measured directly. However, current methods, such as drilling holes through the ice, sample only small areas and provide localised data only.

The ice sheets that blanket Antarctica and Greenland, however, are kilometres thick and it is the melting of these ice masses on land that have a direct influence on sea level. The best approach to measuring these vast thicknesses is to determine the height of the surface.

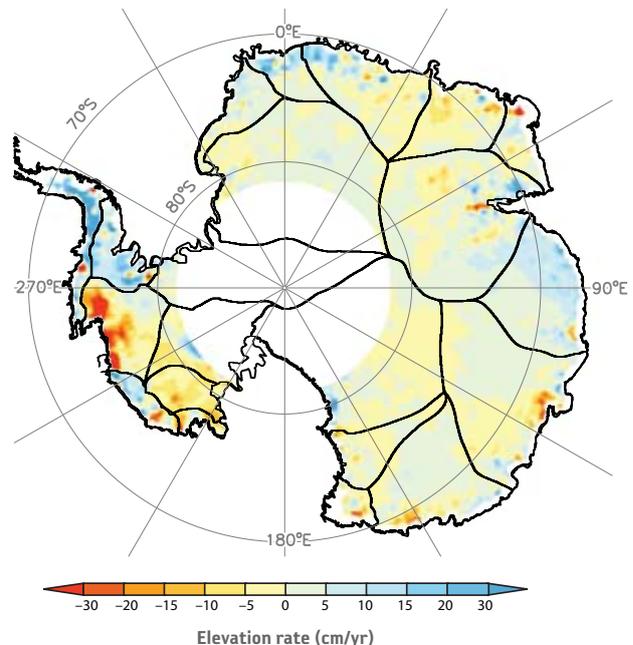
The challenge facing the CryoSat mission falls into two areas. Firstly, to acquire accurate measurements of the thickness of floating sea ice so that annual variations can be detected. Secondly, to survey the surface of the ice sheets accurately enough to detect small changes.

To meet these challenges, CryoSat-2 carries a precise radar altimeter. It sends out short radar pulses and measures the time it takes for the signals to travel from the satellite to the ground and back. Altimeters have become an important tool for oceanographic research. Observations from ESA's Envisat radar altimeter and those on the Jason-2 NASA/CNES Ocean Surface Topography Mission are routinely used for estimating sea-surface and wave heights. Today, the height of sea surfaces can be measured with an accuracy of 2–3 cm.

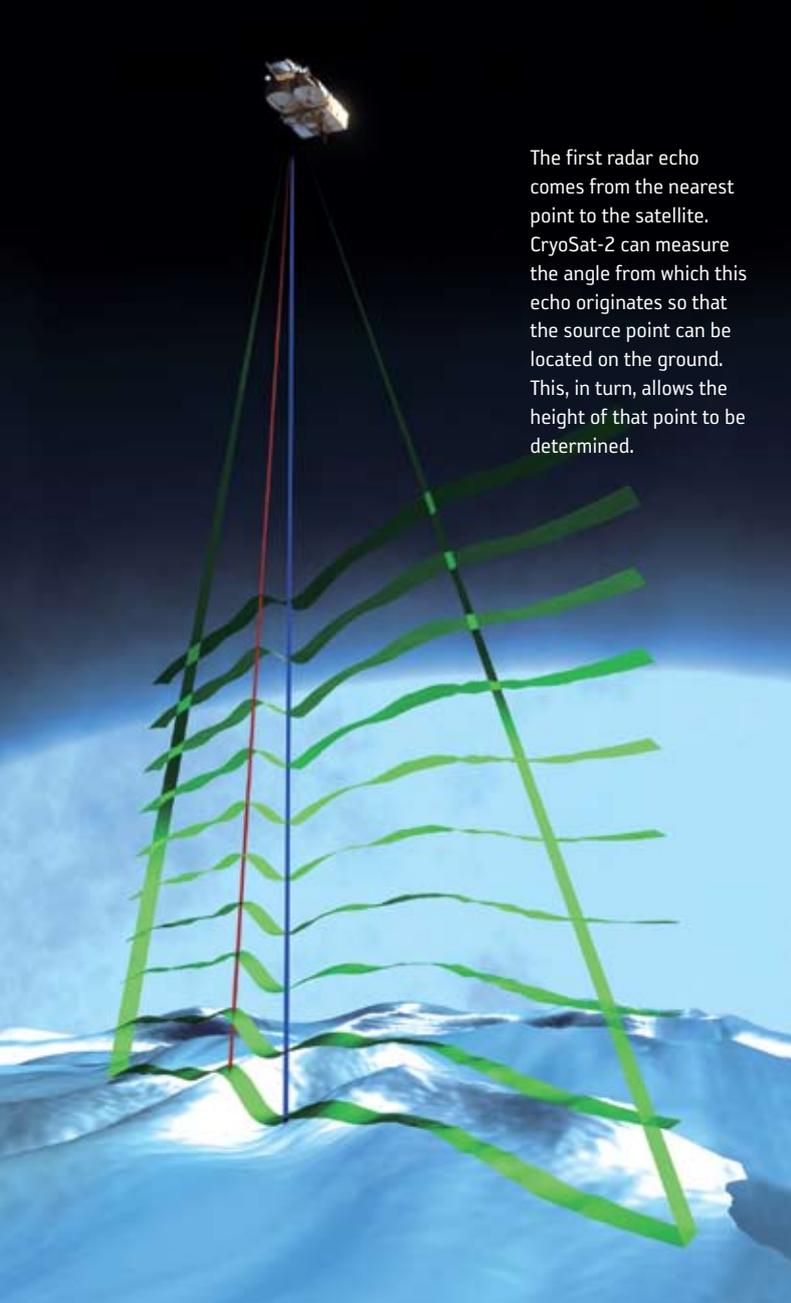
In order to make comprehensive measurements of the polar regions, a radar altimeter needs to have a more specialised design than those currently in orbit. It also has to be carried on a satellite in an unusually high-inclination orbit, to take it very close to the poles. Until the launch of NASA's ICESat, with its laser altimeter, no remote-sensing satellite had ever flown in such an orbit. CryoSat-2 travels even further than ICESat's latitude limit of 86°, reaching 88° north and south on every orbit.



Change in sea-ice thickness for 2007–08, relative to the 2002–08 five-year mean thickness, from Envisat's radar altimeter. Thinning of sea ice in the Beaufort Sea and central Arctic is evident. The area around the pole has no data owing to the latitude limit of Envisat's orbit. (ESA/S. Laxon)



Rate of change in the elevation of the Antarctic ice sheet as measured by satellites carrying radar altimeters. Significant decreases are observed around the coastal ice streams, with the largest loss of ice around Thwaites and Pine Island glaciers in west Antarctica. The white areas around the edges of the ice cap and close to the pole indicate where reliable elevation has not been determined by these earlier missions. The black lines represent primary drainage basins. (D. Wingham et al.)

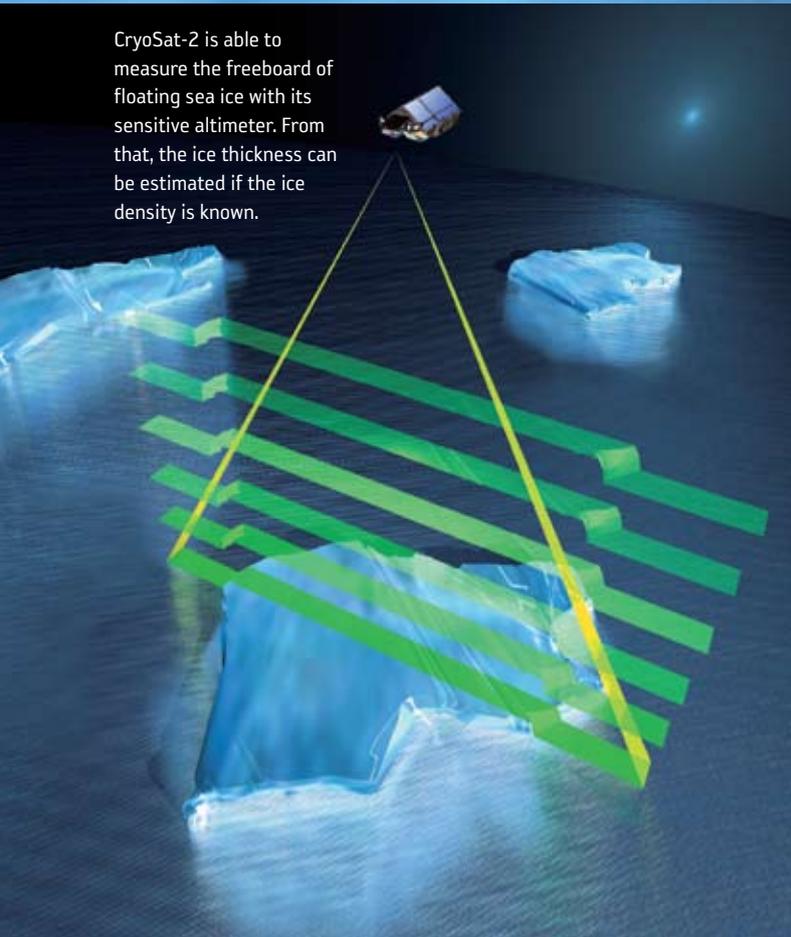


The first radar echo comes from the nearest point to the satellite. CryoSat-2 can measure the angle from which this echo originates so that the source point can be located on the ground. This, in turn, allows the height of that point to be determined.

The surface of the sea is not flat. Although invisible to the eye, the sea surface has ridges and valleys that echo the topography of the ocean floor, but on a greatly reduced scale. The effect of the slight increase in gravity caused by the mass of rock in an undersea mountain is to attract a permanent mound of water several metres high over the seamount. Deep ocean trenches have a surface counterpart, which may be up to 10 m deep. However, spread over a width of 200 km, these features can only be detected by radar altimetry from space. Smaller and more transient deviations from 'sea level' are caused by a range of phenomena, such as tides and ocean currents.

The answer

The current constraints are overcome with the altimeter designed for CryoSat-2, which exploits sophisticated radar techniques to improve resolution and observing capabilities. The mission will provide estimates of sea-ice thickness for the whole of the Arctic basin and monitor thickness changes in ice sheets, particularly around the edges, where icebergs break off as glaciers reach the open sea. Although the satellite is planned to be operational for only three years initially, the accuracy of its measurements will be sufficient to detect evidence of thinning ice sheets and trends in the annual freezing and melting cycles of sea ice. Together with observations of ice extent, this will lead to a better understanding of how the volume of ice is changing.



CryoSat-2 is able to measure the freeboard of floating sea ice with its sensitive altimeter. From that, the ice thickness can be estimated if the ice density is known.

The radar altimeter on Cryosat-2 is based on heritage from existing instruments, but with several major enhancements to overcome the difficulties intrinsic to the precise measurement of icy surfaces. CryoSat-2 determines the thickness of floating sea ice by measuring the 'freeboard' of ice floes – the height protruding from the water. The key to the mission's ability to measure sea-ice thickness all over the Arctic Ocean is high spatial resolution in the along-track direction, which is achieved by the 'synthetic aperture' technique.

The first returning energy in the radar echo comes from the part of Earth's surface closest to the satellite. Over sea ice and ocean, this point is directly below the satellite, but on sloping surfaces, such as those found around the edges of ice sheets, this nearest point can be anywhere. A conventional radar altimeter can determine the range from the satellite to the nearest point very accurately, but as there is no way of knowing where the point is, it is impossible to ascribe a position and elevation to it. CryoSat-2 is able to pin down the location of the echo in the fore- and aft-direction by using its Synthetic Aperture Radar (SAR) capability. To resolve left and right needs an additional feature: over these sloping surfaces the 'SAR-Interferometry' mode provides the key measurements of the angle of arrival of the echo.

→ THE MISSION



CryoSat-2 was taken into orbit on a Dnepr launch vehicle. Unusually, the upper stage flies backwards before releasing the satellite, ensuring the most accurate orbit injection. Launch was from Baikonur Cosmodrome in Kazakhstan. (ESA/P. Carril)



The single ground station for the CryoSat mission is at Kiruna in northern Sweden. The station is linked to ESOC, ESA's European Space Operations Centre in Darmstadt, Germany for controlling and monitoring the satellite. The science data processing is done locally at the Kiruna station by an automated system. (Kiruna Ground Station Team)

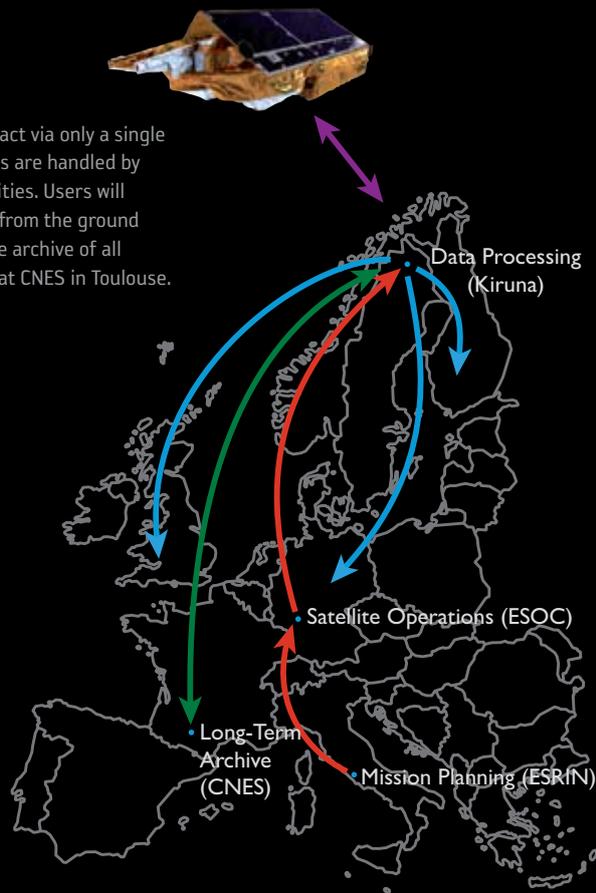
The overall CryoSat mission combines many interdependent parts. To get into orbit, the satellite needs a launcher; it was this that went wrong for the first CryoSat satellite. This time, a different launcher was used, not because of lingering doubts but due to unavailability of the vehicle used previously. So CryoSat-2 was launched by a Dnepr, adapted from the SS-18 intercontinental ballistic missile. Owing to this heritage, the launch was from a silo in Baikonur, Kazakhstan, with ejection by a spectacular explosive charge before the engines ignited some tens of metres in the air. Also unusually, the upper stage flew backwards, dragging the satellite behind it to ensure the most accurate orbit injection.

As soon as the satellite separated it sprang into life: its computer, merely monitoring the satellite during launch, started issuing commands and, in particular, switched on its radio transmitter so that the control team at ESA's ESOC establishment, in Darmstadt, Germany, could establish two-way communications. The first few days of the mission were critical, with the ESOC team working 24 hours per day to ensure the new satellite was fully functional and ready to perform its mission. After this intense period, the operations became more routine, but the flight control team at ESOC continue their work, every day, monitoring and commanding, to keep the system running as it should.

Among the commands the ESOC team sends are those to tell the SIRAL radar altimeter which of its operations modes to use as it flies over different surfaces on the Earth below. The decision is based on a master map maintained in a dedicated planning facility at ESA's ESRIN establishment in Frascati, Italy. Every week the satellite's track over this map is computed and the times when it should switch between the different modes are calculated. This list is then sent to ESOC to be integrated with all the other satellite commands. As ESOC is located at a mid-latitude, the CryoSat orbit passes within range only a few times a day. It is therefore necessary to use an antenna in the far north of Sweden, at Kiruna, to be able to contact the satellite often enough.



CryoSat-2 is in ground contact via only a single station at Kiruna; operations are handled by ESA's ESOC and ESRIN facilities. Users will access data directly by FTP from the ground station itself, and an off-line archive of all mission data is maintained at CNES in Toulouse. (ESA/R. Francis)



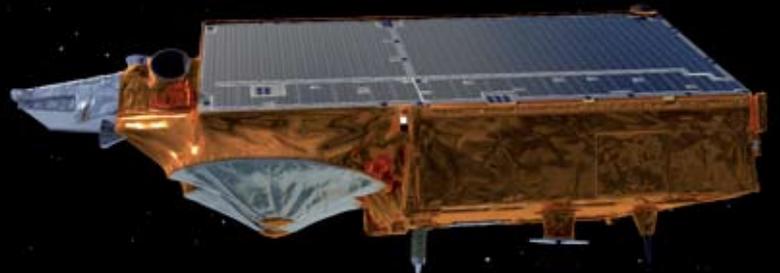
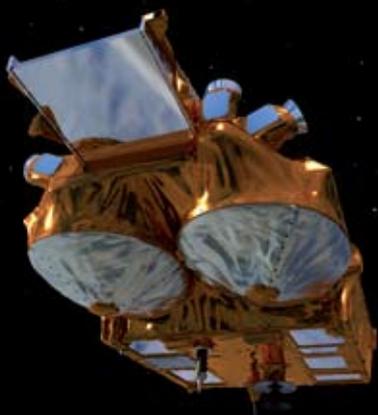
CryoSat-2 at IABG in Ottobrunn, Germany. (ESA/S. Corvaja)



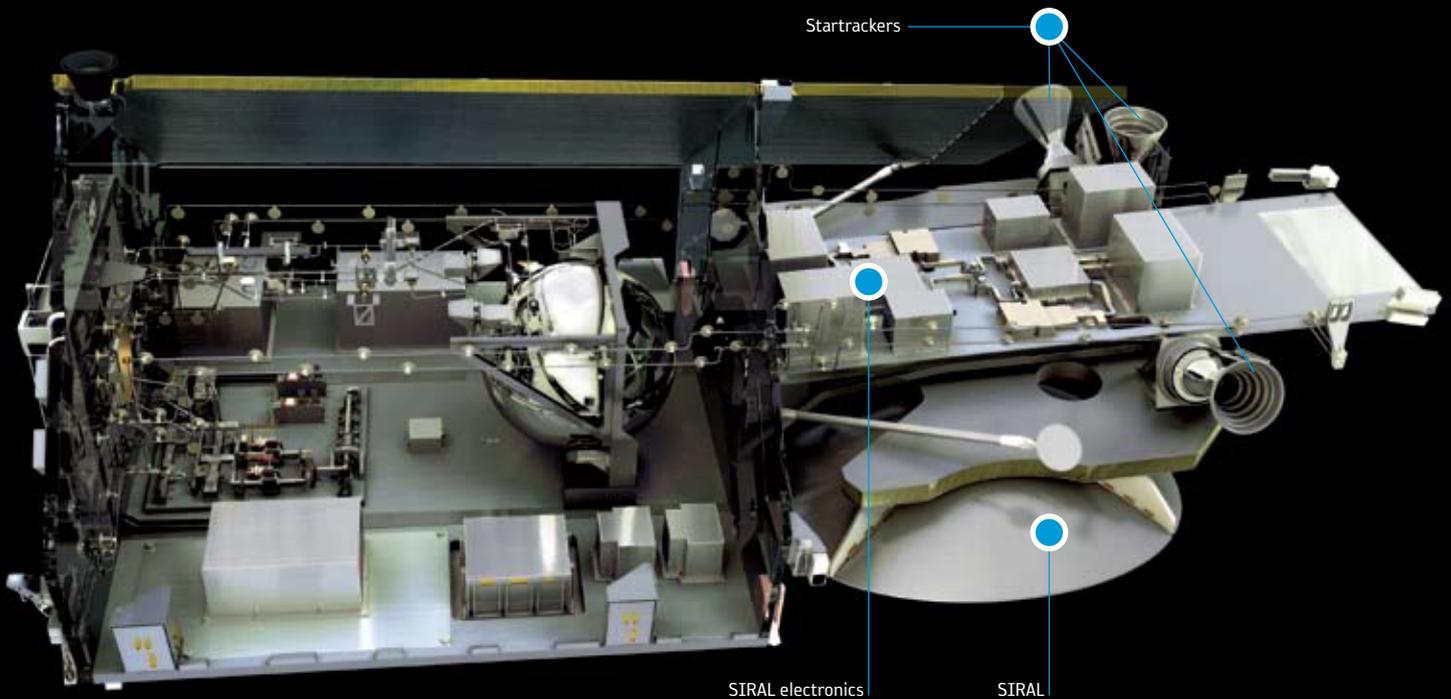
The CryoSat-2 Mission Control Team in the Main Control Room at ESOC. (ESA/R. Francis)

As well as command and control, the Kiruna station is also where the flood of scientific data is received. At more than 50 Gbytes per day, it is a challenge to handle and process it all. While some of the processed data are available almost immediately to the team monitoring how the mission is performing, the scientific users need accurate orbits and other environmental data to be able to exploit the altimeter measurements fully. Until these are available, which can take up to a month, the final data products have to wait.

Every user of the CryoSat mission can access the final data products directly at the Kiruna station, downloading data over the Internet. For the longer term, all of the mission data are archived at a dedicated facility at the Toulouse site of the Centre National d'Etudes Spatiales (CNES). Not only will scientists be able to access the data there in the future, but this centre will also reprocess the whole dataset if improvements in the processing software are developed.



→ THE INSTRUMENTS



CryoSat-2's primary payload is the SAR/Interferometric Radar Altimeter (SIRAL), designed to meet the measurement requirements for ice-sheet elevation and sea-ice freeboard.

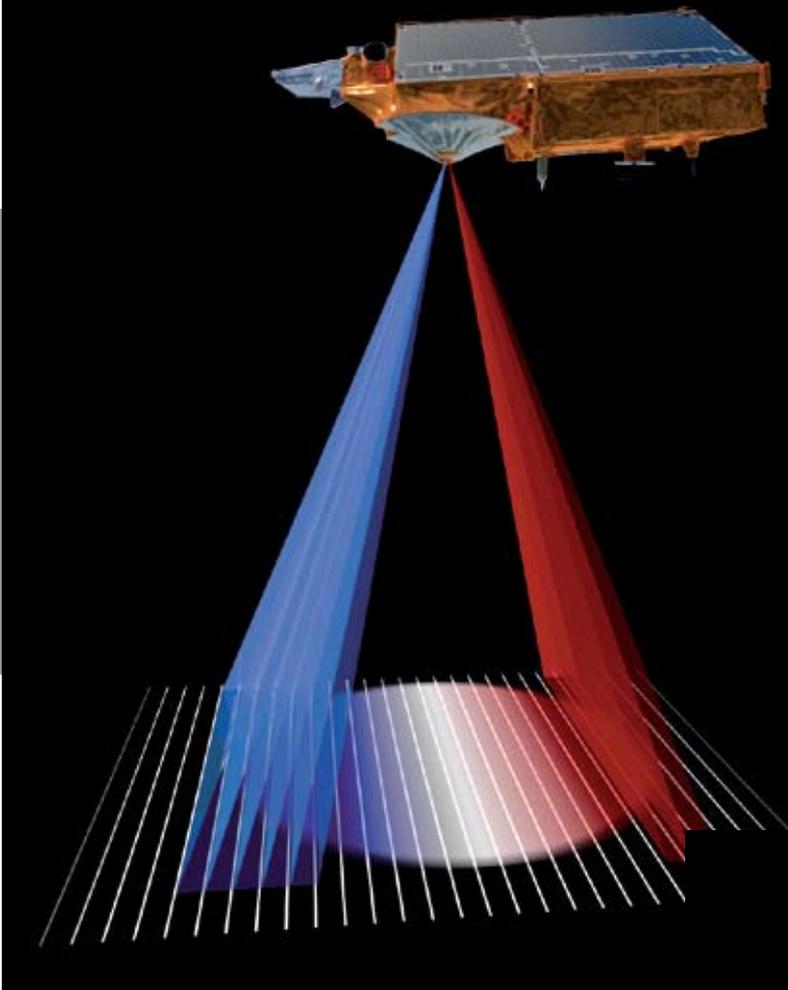
Conventional radar altimeters send pulses at intervals long enough that the echoes are 'uncorrelated'; many such echoes can be averaged to reduce noise. At the typical satellite orbital speed of 7 km/s, the interval between pulses is about 500 μ s. However, the CryoSat-2 altimeter sends a burst of pulses with an interval of only about 50 μ s. The returning echoes are correlated and, by treating the whole burst together, the data processor can separate the echo into strips arranged across the track by exploiting the slight frequency shifts, caused by the Doppler effect, in the forward- and aft-looking parts of the beam. Each strip is about 250 m wide and the interval between bursts is arranged so that the satellite moves forward by 250 m each time. The strips laid down by successive bursts can therefore be superimposed on each other and averaged to reduce noise. This is known as the SAR mode.

In order to measure the arrival angle, a second antenna receives the radar echo simultaneously. When the echo comes from a point not directly beneath the satellite, there is a

difference in the path-length of the radar wave, which is measured. Simple geometry then provides the angle between the 'baseline' joining the antennas and the echo direction. The difference in path length is tiny – up to a wavelength of the radar wave (2.2 cm) – and has to be accurately determined in an overall range measurement of 720 km.

In addition to the altimeter, knowledge of the precise orientation of the baseline of the two receiving antennas is essential. CryoSat-2 measures this baseline orientation using the oldest and most accurate of references: the position of the stars in the sky. Three startrackers mounted on the antenna support structure each takes five pictures per second. Each image is analysed by the startracker's built-in computer and compared to a catalogue of star positions.

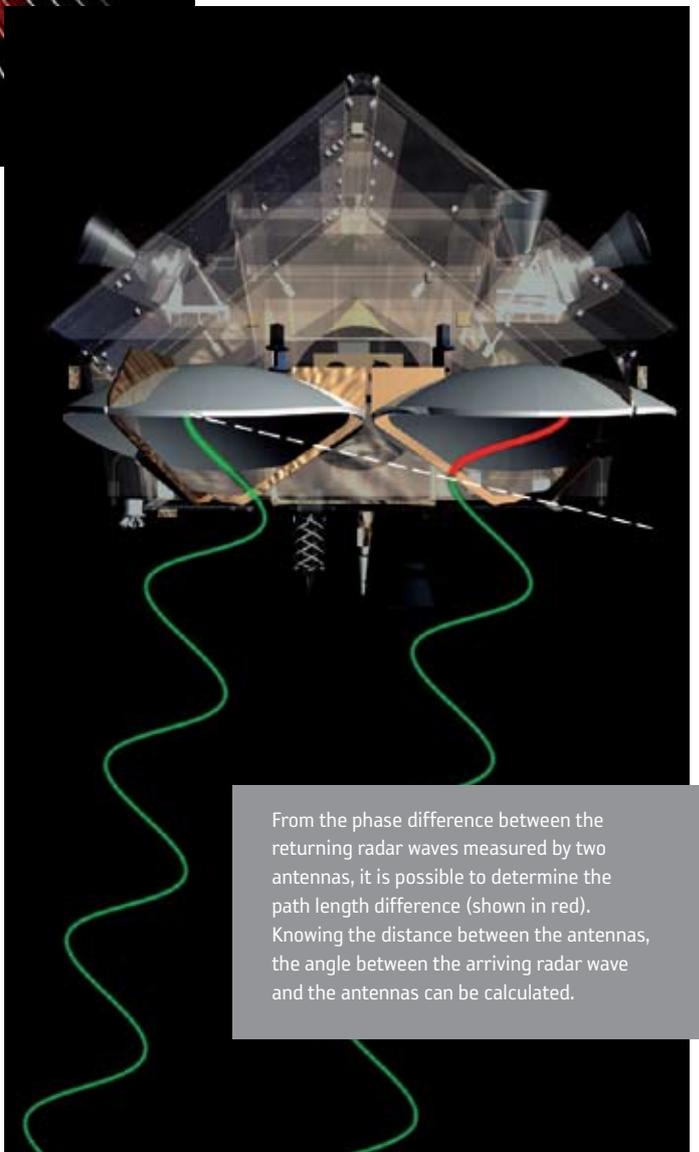
The altimeter makes a measurement of the distance between the satellite and the surface. However, this measurement cannot be converted into the more useful measure of the height of the surface until the satellite's position is accurately known. These days, the orbital position of altimetry satellites can be determined to within a few centimetres. To do this, CryoSat-2 carries two devices: a radio receiver and a laser retroreflector.



The footprint of the radar beam on the ground reaches partly ahead of the satellite and partly behind it. The satellite moves at high speed in its orbit, towards some of the footprint and away from others. This relative speed induces slight frequency shifts in the returning radar energy, owing to the Doppler effect, shown as blue or red tint here. The radar echo contains the combination of all this energy but, by processing a correlated burst of radar pulses, it is possible to slice up the returning echo into a series of Doppler beams.

The Doppler Orbit and Radio Positioning Integration by Satellite (DORIS) radio receiver detects and measures the Doppler shift on signals broadcast from a network of more than 50 radio beacons around the world. Although the full accuracy of this system is obtained only after ground processing, DORIS provides a realtime estimate on board, good to about half a metre. The DORIS system has been operating for more than a decade, and is used on many satellites, such as Envisat.

The small laser retroreflector is attached to the underside of CryoSat-2. This little device has seven optical corner cubes, which reflect light in exactly the direction it came from. A global network of laser tracking stations fires short laser pulses at CryoSat-2 and times the interval before the reflected pulse arrives back. These stations are relatively few but, because their positions are very accurately known, from their routine work of tracking geodetic satellites, they provide a set of independent reference measurements of CryoSat-2's position.



From the phase difference between the returning radar waves measured by two antennas, it is possible to determine the path length difference (shown in red). Knowing the distance between the antennas, the angle between the arriving radar wave and the antennas can be calculated.

→ THE ESSENTIAL GROUNDWORK

Given that the aim of the CryoSat mission is to measure global changes in ice thickness down to a few centimetres per year using its sophisticated SIRAL radar altimeter, it is hardly surprising that a lot of effort goes into ensuring the data are as accurate as possible and that all possible errors are accounted for.

There are a number of ways in which errors could creep into the resulting ice-thickness maps. For example, snow layers are unavoidable when observing icy surfaces so the influence they have on the measurements taken by CryoSat-2 has to be assessed very carefully. There are many other potential error sources, including changes in snow wetness with time, the weight of snow on top of sea ice and variations in snow and ice density over a particular area.

To understand and correct for such natural sources of error means that large-scale expeditions to the polar regions have to be undertaken to collect information on snow and ice properties. These expeditions are needed both before launch, as essential input to the software that will transform CryoSat-2's measurements into ice-thickness maps, and after launch in order to make a direct comparison between ground and satellite measurements.

ESA has organised a number of these Arctic and Antarctic expeditions. They are huge logistical undertakings, often involving taking simultaneous measurements from the air and on the ground by a large number of scientists. On the ground, sophisticated equipment such as ground-radar and neutron probes, as well as more traditional techniques, such as digging snow pits and drilling through the ice, are used to measure snow and ice properties. Data are also taken from an aircraft carrying a radar instrument very similar to that on the satellite. These airborne data are then compared to the measurements taken on the ground and to the actual satellite measurements to fully understand and correct for the main error sources.

In addition to the large expeditions organised by ESA, several polar explorers, inspired by the CryoSat mission, have also volunteered to contribute by taking snow-depth and other measurements during their treks across the Arctic.

All this groundwork represents an essential part of the mission and the data collected allow scientists to interpret accurately the variations in ice thickness with time observed by CryoSat-2 so that the best possible trend in ice-thickness change over time can be derived.





A Dornier-228 aircraft from the Alfred Wegner Institute carrying the 'ASIRAS' airborne version of CryoSat-2's radar altimeter. The rectangular antenna is visible under the fuselage. It provides, together with a laser scanner, the basic measurements required for CryoSat-2 validation. (ESA/M. Davidson)



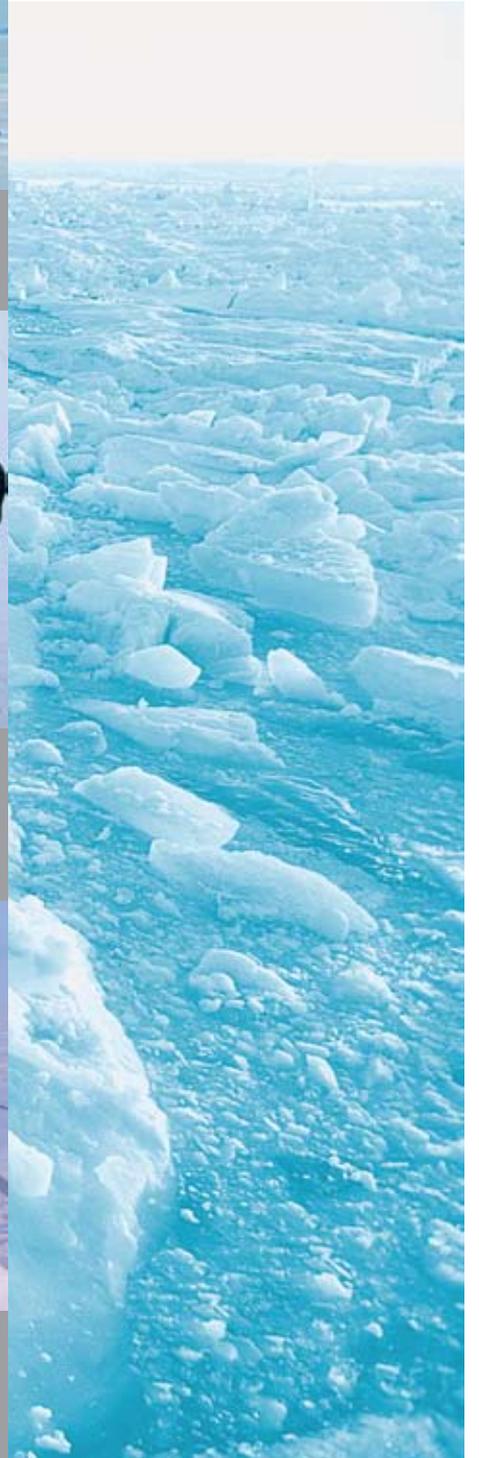
Camp in Dronning Maud Land, Antarctica, where measurements of a 'blue ice' region, clear of snow, were made. (Technische Universität Dresden)



Corner reflectors are used extensively during CryoSat validation campaigns. Their metallic structures reflect the radar pulses emitted by the airborne ASIRAS. They are used to verify the quality of the airborne data and to understand how the radar signal penetrates the snow and ice surface. (Norwegian Polar Institute)



A neutron probe is lowered into a hole drilled in the ice. It collects essential data on snow and ice density layering to help understand the observed radar altimeter signal and ultimately transform the height measurements into net change in ice mass, the main goal of CryoSat over land ice. (Norwegian Polar Institute)



→ CRYOSAT-2 OVERVIEW

The CryoSat mission will determine variations in the thickness of continental ice sheets and floating sea ice to understand how Earth's ice is responding to climate change. The CryoSat-2 satellite replaces the original CryoSat, lost in the 2005 launch failure.

Mission

Launch: April 2010

Duration: 3 years (following 6-month commissioning phase); satellite upgraded to a 5-year life

Objectives

To measure changes in ice thickness to an accuracy of about 10% of the expected interannual variation. Over sea ice, this corresponds to about 1.5 cm/year, while over small areas of ice sheets it is about 3 cm/year. Integrated over the whole of Greenland, the required accuracy is 0.7 cm/year. The mission comfortably meets these requirements

Orbit

Type: low Earth, polar, non-Sun-synchronous

Mean altitude: 717 km

Inclination: 92°

Payload

SAR Interferometric Radar Altimeter (SIRAL), supported by Doppler Orbit and Radio Positioning Integration by Satellite (DORIS) and Laser Retro-Reflector (LRR) for precision orbit determination

Configuration

Simplified rigid structure with no moving parts, overall 4.6 × 2.4 × 2.2 m

Mass

720 kg at launch, including 37 kg of propellant

Power

2 GaAs body-mounted solar arrays, each delivering 850 W;

78 Ah Li-ion battery

Attitude

– 3-axis stabilised local-normal pointing, with 6° nose-down attitude

– Startrackers, magnetometers, magnetotorquers and 10 mN cold-gas thrusters

– <0.25° pointing error

Command and Control

Integrated data handling and Attitude and Orbit Control System computer with communication via a 1553 bus and serial links

Onboard Storage

– Solid-state recorder, capacity 2 × 128 Gbit

– Payload data generated on board: 400 Gbit/day

– Full mission operations with single ground station at Kiruna, SE

Communication Links

– X-band downlink for science data to Kiruna (100 Mbit/s at 8.1 GHz)

– S-band uplink (2 kbit/s) and downlink (16 kbit/s) to Kiruna for satellite telemetry and telecommand

Flight Operations

– Mission control from ESA's European Space Operations

Centre (ESOC) in Darmstadt, DE, via Kiruna ground station

– Measurements planned at ESA's Centre for Earth

Observation (ESRIN) in Frascati, IT, according to a

geographically defined mask

Data Processing

– Data processing facility at Kiruna ground station

– Local archiving of data with processing after 1 month

following delivery of precise orbits from Centre National d'Etudes Spatiales (CNES) in Toulouse, FR

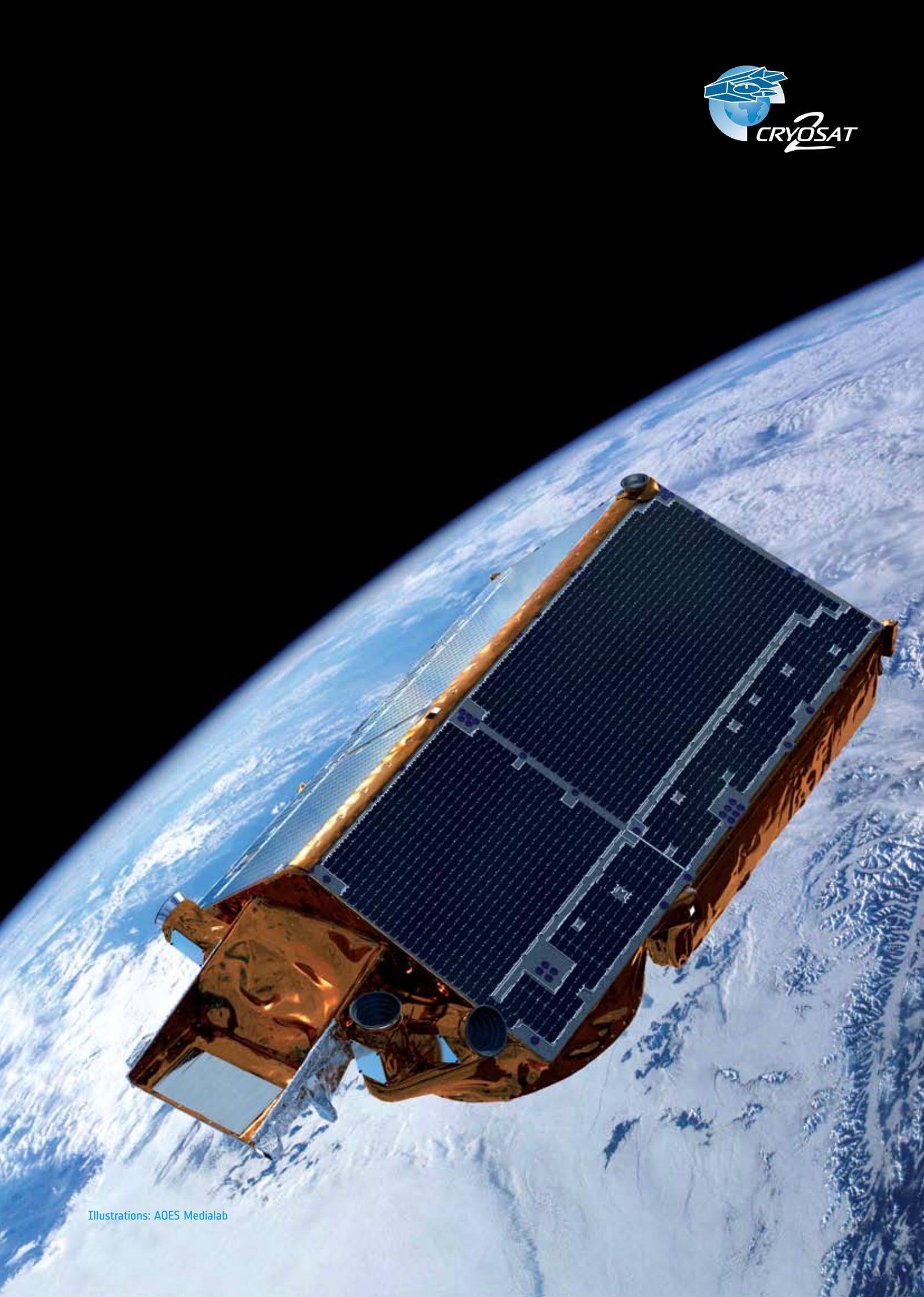
– Possibility of quick-look data

– Long-term archive at CNES

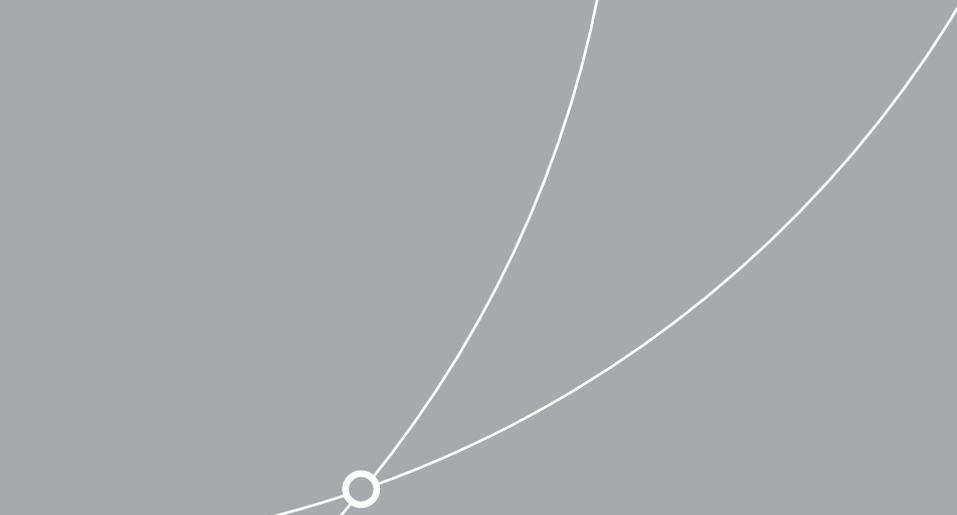
– User services coordinated via ESRIN

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