→ ESA'S ICE MISSION

CryoSat: more important than ever

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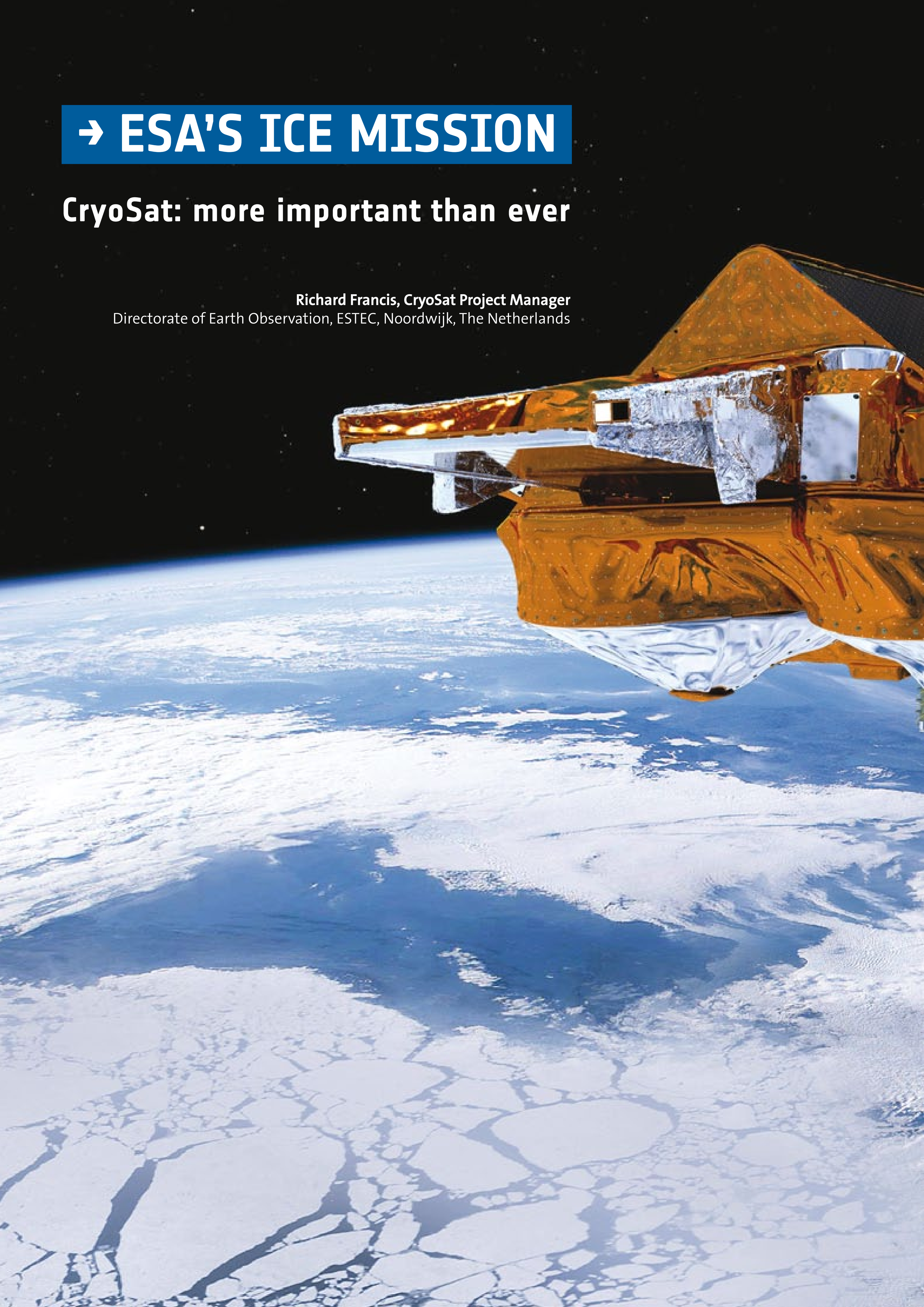

In 2005, the first CryoSat satellite was destroyed in a launch failure. However, following its loss, the mission was judged to be even more important than when it had first been selected, and approval to rebuild the satellite was secured within a record-breaking four months.

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The launch of CryoSat in October 2005

During the evening of 8 October 2005, a Rockot launch vehicle lifted off from the Plesetsk Cosmodrome, some 800 km north of Moscow. This rocket was carrying CryoSat, ESA's first Earth Explorer 'Opportunity' satellite intended to measure changes in the thickness of Earth's ice fields: both ice caps – thick domes of ice resting on land – and sea ice floating in polar oceans.

As expected, telemetry was lost from the launcher some eight minutes later as it travelled towards the North Pole, out of range of the receiving station at Plesetsk. After passing into radio silence, there were almost 90 minutes to wait before we could expect the upper composite of CryoSat and the rocket's third stage to travel around the Earth and into range of the Redu ground station in Belgium, with slightly later acquisition at Villafranca in Spain and then Kiruna in Sweden.

Separation from the third stage would occur five minutes after this acquisition of signal, when the satellite would be in range of Kiruna.

No signal was received.

The ground stations tried to acquire the signal, some using a search pattern to 'sweep' the expected region of the sky. Then a series of 'blind' telecommands was sent in an attempt to reconfigure the satellite's telemetry system. Searching and commanding was continued from four ground stations (including Svalbard, which was due to acquire after Kiruna) for the duration of the nominal pass: almost 20 minutes.

It proved impossible to learn whether the launcher authorities had received any signal from the third stage, so we were unable to tell if it was a satellite failure, a launch into a grossly wrong orbit or a launch failure. The Flight Dynamics team at ESOC in Germany computed a possible orbit, based on a theoretical failure of the apogee boost burn of the third stage. So, in the second pass, over an hour after the first, the four ground stations made a search based on this orbit and again sent blind commands to reconfigure the telemetry system.

But now, some three hours after launch, reports started appearing on the Internet of a launch failure. A specific failure mechanism was identified, which lent them credibility. Nevertheless, ESOC continued trying to contact the satellite even though the prospects of success were bleak. Eventually, about four hours after launch, the Russian authorities made their first announcement of a launch failure. The Internet reports were confirmed.

CryoSat background

ESA Bulletin 122, May 2005 (www.esa.int/SPECIALS/ESA_Publications/SEMLML6DIAE_0.html)
More information at: www.esa.int/cryosat

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The last view of CryoSat, only minutes before it was destroyed

Fiery destruction

After liftoff, the Rockot launcher had discarded its first-stage booster and then the fairing, which protects the payload during its ascent through the atmosphere. At 298 seconds after launch, the shutdown of the second-stage cruise engine was due, before its separation. However, the command for this shutdown was not sent to the second stage, so the engine continued to burn until all its fuel was used up. This resulted in an unknown, but catastrophic, event that started a severe tumbling motion.

Some 10 seconds later, the deviation in pitch exceeded the specified limits: this was the trigger to issue a mission failure command from the onboard computer. All further onboard commands stopped and the composite of second stage, a fully fuelled third stage and CryoSat continued on an unpowered ballistic trajectory, tumbling in all axes.

At the time of the failure, this composite was travelling at more than 5 kilometres per second (18 000 km/h), at a height of almost 200 km. The spacecraft effectively underwent a full reentry into the atmosphere, combining severe g-forces, continued tumbling and the fury of reentry heating. Somewhere in the upper stratosphere, this punishing combination inevitably caused a rupture of the fuel tanks in the vehicle's third stage.

The full load of propellant then exploded, completing the job of destroying CryoSat. The remains fell within the planned second-stage drop zone, close to the North Pole, just over 12 minutes after liftoff. The subsequent investigation rapidly identified the cause of the failure: two onboard commands had been incorrectly juxtaposed. The error was undetected because of inadequate testing: the validation process used was unable to detect this fatal condition.

Picking up the pieces

Following the failure, there was an immediate consensus that the lost satellite should be replaced. But transforming that consensus into a practical implementation required considerable effort and goodwill from all those involved: industry, the science community, the delegations of our Member States and ESA.

Resources needed to be found. It was important to demonstrate that funding would not require any 'new' money. By reallocating some existing budgets, delaying some activities and exploiting synergies, this turned out to be possible. Another important resource was staff: most of the team had already been earmarked for other projects, but again this was solved.

We also had to move quickly to set up the legal and contractual basis of the project. Almost immediately we were able to order the 'long-lead items', that is, items that have a long delivery time. Some of the high-reliability electronic parts have delivery times of up to a year, so ordering early would be very important to maintain a reasonable schedule.

A significant coordinated effort was needed to establish all of the technical documents that define the industrial work (which is necessarily different for a rebuild), the preparation of a binding offer by industry, and the evaluation and eventual negotiation of this offer. In preparing these documents, a fundamental question was the extent to which improvements in the satellite might be implemented.

The main payload, the SAR/Interferometric Radar Altimeter (SIRAL), had been the only single instrument on the original CryoSat, and it was full of 'single-point failures', that is, single components whose failure would cause the loss of the whole instrument. It was an easy decision.

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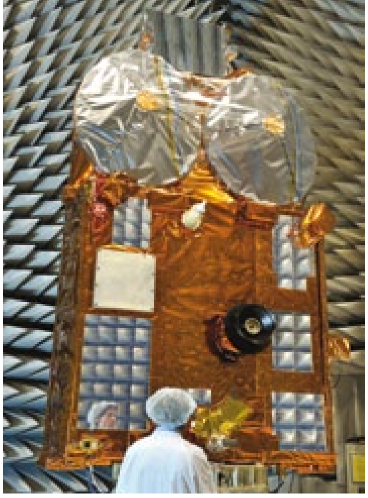
CryoSat-2 during testing at IABG



We would implement full redundancy in this payload. Parts of the original satellite design were obsolete, both at the level of components and in some complete pieces of equipment. Here there were no options: they had to be replaced by current designs. With these changes in place, it was a minor decision to rectify a number of shortcomings in the original design, found during system testing and to make improvements in operability of the satellite. Usually these improvements took the form of small changes to the central flight software.

→ CryoSat more important now than ever

It is over ten years since Prof. Duncan Wingham (Professor of Climate Physics and Head of Earth Sciences at University College London) first proposed the CryoSat mission. It was selected from about 30 proposals to become ESA's first Earth Explorer Opportunity mission. Our level of knowledge about the polar regions has changed a lot during this time, and, for that matter, so have the polar regions themselves. In 2006, during the process of approving the rebuild, the question was first raised, "Is CryoSat still relevant?" The unequivocal response from independent scientific advisors was, "CryoSat is more important now than when it was first selected."

Almost four years after that statement, the situation is still evolving. On one hand, the signs of change in the polar regions continue unabated, while on the other, our ability to extract subtle details from satellite data is still improving.

→ A decade of climate change

One of the most dramatic signs of climate change is in the extent of Arctic sea ice. Since 2000, the area covered by sea ice in the summer has reduced drastically. The absolute minimum occurred in September 2007, and 2008 would have been a new record if it had not been for 2007, and 2009 was similar. These great reductions in the area of sea ice in the middle of the summer are much worse than expected if we simply extrapolated from the previous trends.

There are several factors involved: the prevailing winds have a great influence (floating ice can be simply blown out of the Arctic Ocean, passing Greenland and Iceland and disappearing into the Atlantic). Thermodynamics is also playing a role: as the amount of ice reduces, more heat is absorbed by the ocean in summer, and consequently less ice formed by freezing in winter, accelerating the trend in reducing ice cover.

While these reductions in the area of sea ice are readily observable using a variety of satellite remote-sensing techniques, there is only one practical way of converting this knowledge of sea-ice area into the *amount* of sea ice. We need information about the thickness of the ice, and the only way to measure that on a large scale is by satellite. This is where CryoSat comes in.

Apart from floating sea ice, the other characteristic manifestations of ice in polar regions are the ice caps: thick domes of ice resting on land, from relatively small islands up to the complete continent of Antarctica. The two largest, Antarctica itself and Greenland, are several kilometres thick and, at the summits, very cold.

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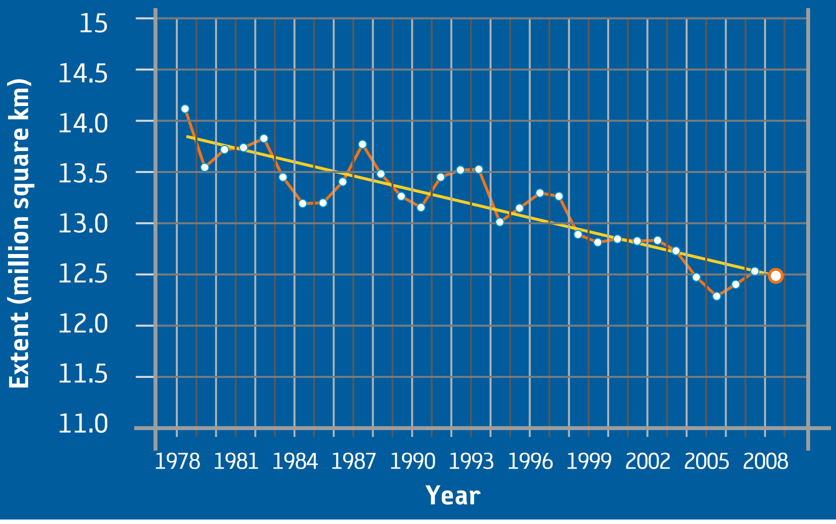
Monthly December ice extent for 1979 to 2009, showing a decline of 3.3% per decade. December 2009 had the fourth-lowest average ice extent since the beginning of satellite records (NSIDC)



Some updates were required in the ground segment too. These were partly a direct consequence of the updates in the satellite design: for example, a means of handling the two redundant radar systems had to be developed and implemented.

Other changes were needed to avoid obsolescence and to improve the way corrections for environmental effects are made, in common with other satellites such as Envisat.

A better CryoSat

The radar on the original CryoSat was 'non-redundant'. If any part failed, there was no back-up and the radar would stop working. Of course, the electronics had very high reliability, but you can never be sure that a random failure, however unlikely, would not happen. This contrasted with the rest of the satellite where there was spare equipment for every function. This follows normal practice with space missions.

Thus they may seem immune to the influence of a few degrees of global temperature rise. Indeed, prior to 2000 the indications were that these major ice-caps were largely stable, at least in their interiors. The principal means of determining this was, again, satellite altimetry. However, the capabilities of such instruments to measure change at the ice cap margins, where most change is expected, is limited by their design.

But, already by 2006, skilled analysis of the existing altimeter data was teasing out details that were beginning to cast doubt on this picture of stability. A very large glacial basin at the coastal boundary of West Antarctica, the Pine Island Glacier, was sufficiently large that it could be resolved in the conventional altimeter data. And the ice was thinning.

In the years since 2006, this thinning has been characterised and linked to Synthetic Aperture Radar (SAR) interferometry measurements of ice flow, which show an increased flow rate into the sea. The rate of thinning is stunning, at about 16 m per year.

While this has been reported by several groups, it has been put into perspective by the late-2009 report by the Scientific Committee on Antarctic Research, *Antarctic Climate Change and the Environment*, which projects a sea-level rise of about 1.4 m by 2100, significantly higher than the well-known 28–43 cm projections of the Intergovernmental Panel on Climate Change. The difference is largely attributable to melting of the ice-caps at their base by warming oceans.

Change is not limited to Antarctica. Greenland, being smaller and at lower latitudes, may be even more vulnerable. Gravity measurements from the NASA/DLR GRACE mission have revealed large-scale mass changes and even sensitive GPS receivers placed around the coast show signs of uplift as the burden of ice is reduced.

So indeed, in the decade since the CryoSat mission was proposed, the signs of change in the polar regions have become unambiguous and this trend is also clear in the four years since CryoSat-2 was approved.

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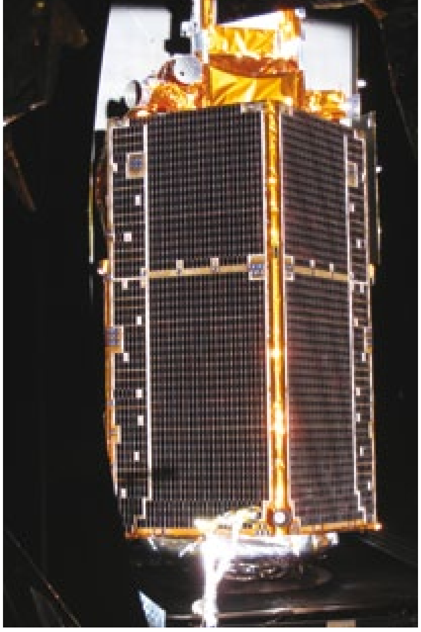
Antarctic ice meets the ocean, Pine Island Glacier seen from the air in November 2009 (Jim Yungel/NASA)



CryoSat-2 in the solar simulation chamber at IABG's facilities in Ottobrunn, Germany, 2009

The reason why the SIRAL was non-redundant was simply down to cost. The radar represented a significant portion of the overall cost and providing an onboard spare would have exceeded the strict limit on cost placed on the mission. This decision was hotly debated during the development phase, and it was perhaps this debate that triggered one comment after the launch failure, that "Non-redundancy saved us quite a lot of money!"

There was, however, no debate when it came to the rebuild. If we could afford to rebuild the mission, we could not afford to risk losing it again due to a single component failure. So CryoSat-2 carries a redundant SIRAL. This has introduced a few complications.

→ So how will CryoSat help?

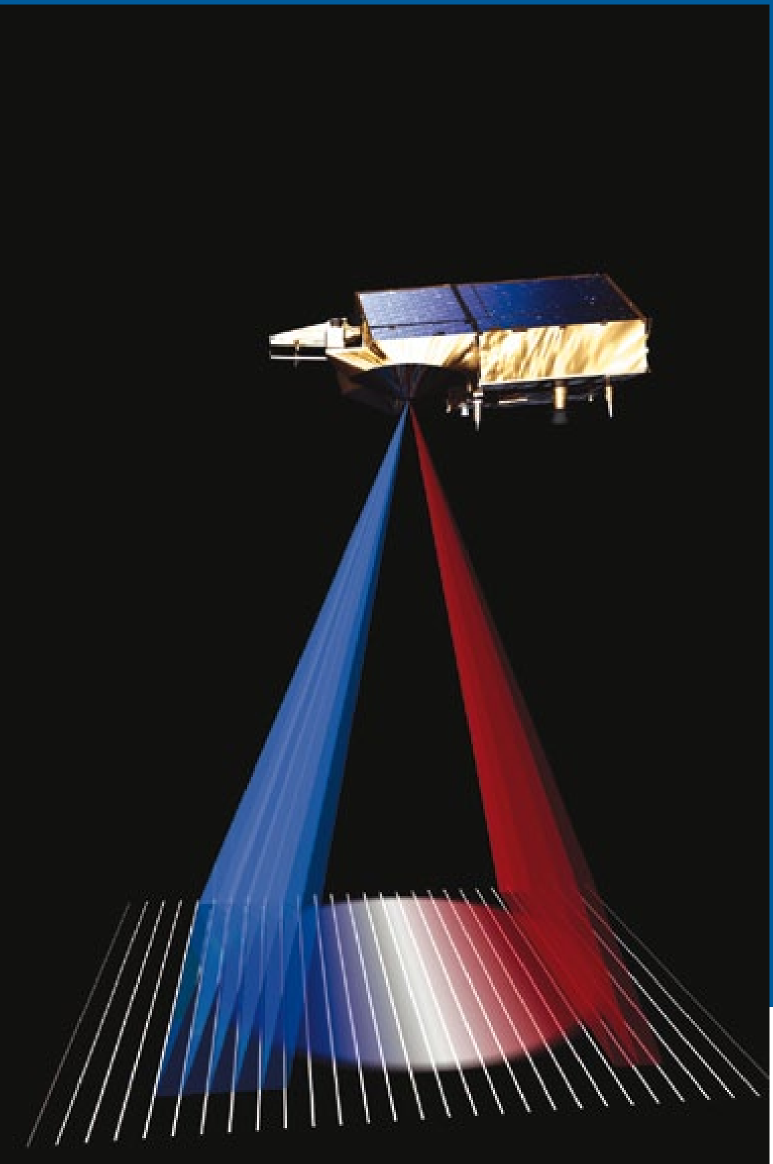
When it was proposed, the objective of CryoSat was to distinguish between the genuine trends in ice thickness and, quoting the proposal, 'the ephemera of inter-annual variation'. Ten years on, there seems little doubt that there are trends: now the challenge is to better characterise them, and extend our knowledge to more intractable surfaces.

To understand how a reduction in area of sea ice may be linked to the amount of ice, a means of measuring sea-ice thickness over a large area is needed.

As far back as 1998, Dr Seymour Laxon of University College London developed a way to distinguish between the radar echoes from floating sea ice and those from the ocean in which they float. The difference in height is not much, some tens of centimetres, but using a more elaborate version of the well-known idea that 7/8 of an iceberg is underwater, this measurement enabled the ice thickness to be estimated.

This is fine in theory but, in practice, it has proved tricky to fully exploit the technique, because the 'footprint' of the radar instruments on satellites used so far (ERS and Envisat) is so large that it is difficult to distinguish ice from open water, given that many of the open water 'leads' are relatively narrow. Thus the probability of retrieving the sea-ice thickness is about 0.1 and there are many gaps in the existing measurements.

Given Laxon's success in measuring sea-ice thickness at all, Wingham recognised that the method could be usefully improved by changing the characteristics of the radar, so that the sampling area was very much reduced. Studies of such a radar concept were already under way with European industry. This is one of the several key innovations of the CryoSat mission.



Returning echoes from the radar 'footprint' can be processed to separate them 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 (AOES Medialab)

The number of onboard connections has multiplied significantly: for example, where there were two connections from the main and redundant power source, there are now two for each SIRAL, making four in total. The SIRAL is connected to a lot of other equipment: the central computer, high-speed data lines to the onboard mass memory, a frequency reference from the DORIS receiver, several power supplies, and so on.

There was a further consequence of this decision. The systems on the ground that control the satellite and process its data had been built on the assumption of one radar. Now there are two and, inevitably, they are subtly different.

The timing of the radar pulses is increased so that pulses, sent in rapid bursts, result in echoes that are correlated, since the geometry is effectively frozen during the burst. Then complex processing, exploiting the Doppler properties of the echoes, enables a sharpening of the along-track resolution to about 250 m. This 'synthetic aperture radar' (SAR) mode will enable a great improvement in the discrimination of sea ice and the leads between the floes, with the expectation that the probability of retrieval will be increased.

Combined with an increase of geographic coverage of the CryoSat orbit, extending to latitudes of 88° North and South, compared with 82° for the sun-synchronous ERS and Envisat orbits, this will represent a great improvement of the regions where sea-ice thickness can be reliably determined.

We have already seen that the challenge in understanding changes in the ice caps lies at their edges. Pine Island in Antarctica is a huge drainage basin but there are many smaller ones. The increase in spatial resolution afforded by the SAR mode is a great help but there is also the problem, over such varied topography, that the point we measure today may not be the same point that we measure next time, so that determining the height difference is misleading. This problem arises because the radar altimeter naturally measures range to the closest point on the surface. If the ground track is not identical (and it never is) then such a point may be a hillock to the side of the track, and a different hillock next time.

CryoSat solves this problem with an innovative technique. In a variant of the SAR mode, called the SAR Interferometry mode (SARIn for short), it uses a second antenna and receiver. The phase difference between the signals received by these two systems is a function of the angle of arrival of the echoed signal. With precision electronics and clever data processing, this can be exploited to determine exactly where on the surface the echo came from, allowing a much more confident determination of surface elevation change.

The precision of the measurements made by these radars is astonishing: better than one part in a hundred million, so it is not surprising that subtle differences in their characteristics have to be taken into account.

This is handled by a database of many parameters. But now the ground system had to recognise which radar was providing the data it had to process and call up the correct database.

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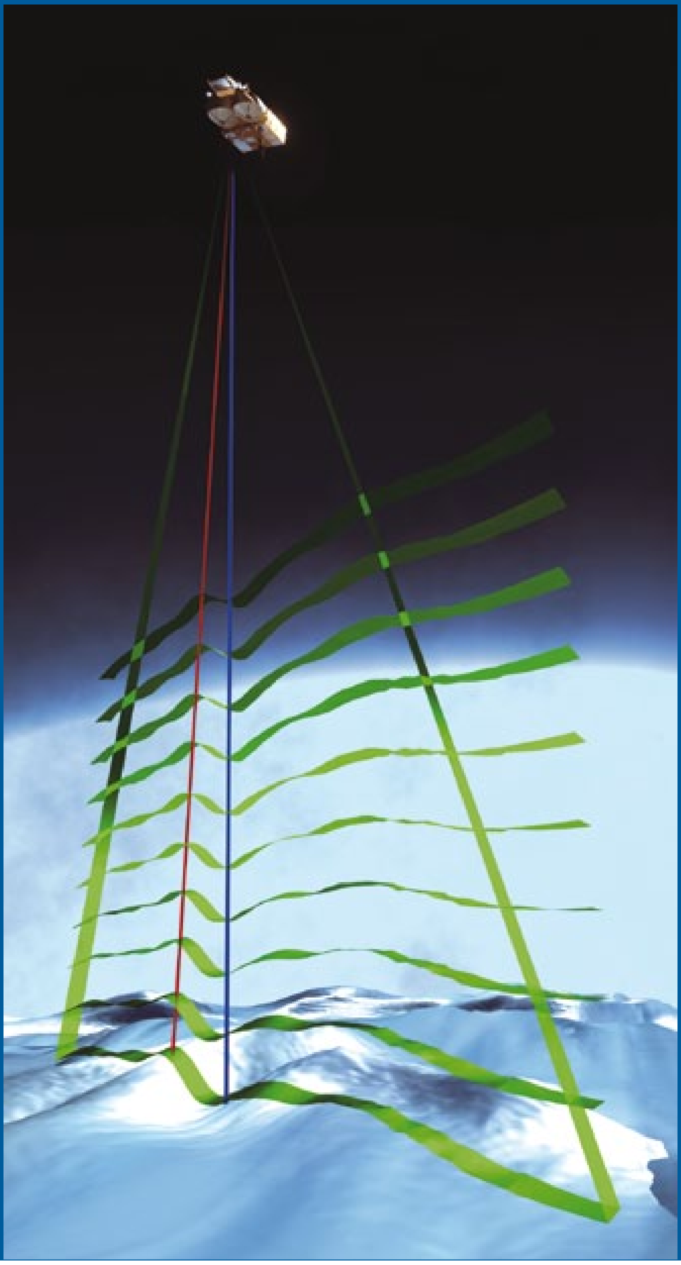
Over topographic surfaces, the first radar echo comes from the nearest point to the satellite. CryoSat can measure the angle from which this echo originates, so that the source point can be located on the ground, allowing the height of that point to be determined (AOES Medialab)



← CryoSat-2 in cleanroom at IABG

→ Launch of a Dnepr rocket (Kosmatras)

This may sound simple, but finding all the places affected, making the process work and testing everything were not so trivial.

There is another, very obvious difference between CryoSat-2 and its earlier sibling. CryoSat-2 will be carried into space on a different launch vehicle. It is misleading to assume that this change was a result of the previous failure. In fact, we were completely satisfied that the cause of the CryoSat launch failure had been effectively found and cured. Indeed, last year, Rockot launch vehicles put two other ESA Earth Explorer satellites into orbit: GOCE in March and SMOS in November 2009.

The problem was instead one of availability. It was not possible to obtain a Rockot within the timescale we needed and so, in early 2008, we switched to a back-up launcher: the Dnepr. Like Rockot, Dnepr is also based on a Russian missile design, in this case the SS-18. Unlike Rockot, it is launched from a silo, being expelled like a mortar round with a charge of black powder, before the main engine ignition some 30 m above the ground. CryoSat-2 will experience this unusual and, we have to admit, rather nerve-wracking launch from the Baikonur Cosmodrome. The launch is scheduled for 25 February.

Four short years

The CryoSat-2 rebuild began in March 2006. In February 2010, just under four years later, it will be launched. Of those four years, the first year was spent consolidating the design updates and starting to build the pieces, leading up to delivery of the structure a year after the kick-off. During the second year, the equipment was delivered and gradually installed and checked out. In the third year, in mid-2008, the satellite was shipped to the test centre in IABG where it remained until being shipped to the launch site in January 2010. The satellite had been in storage for nine months because of the scheduling of the launch.

At the end of a short launch campaign, the satellite will be projected into space, to continue the mission that was so unfortunately interrupted in October 2005. ■