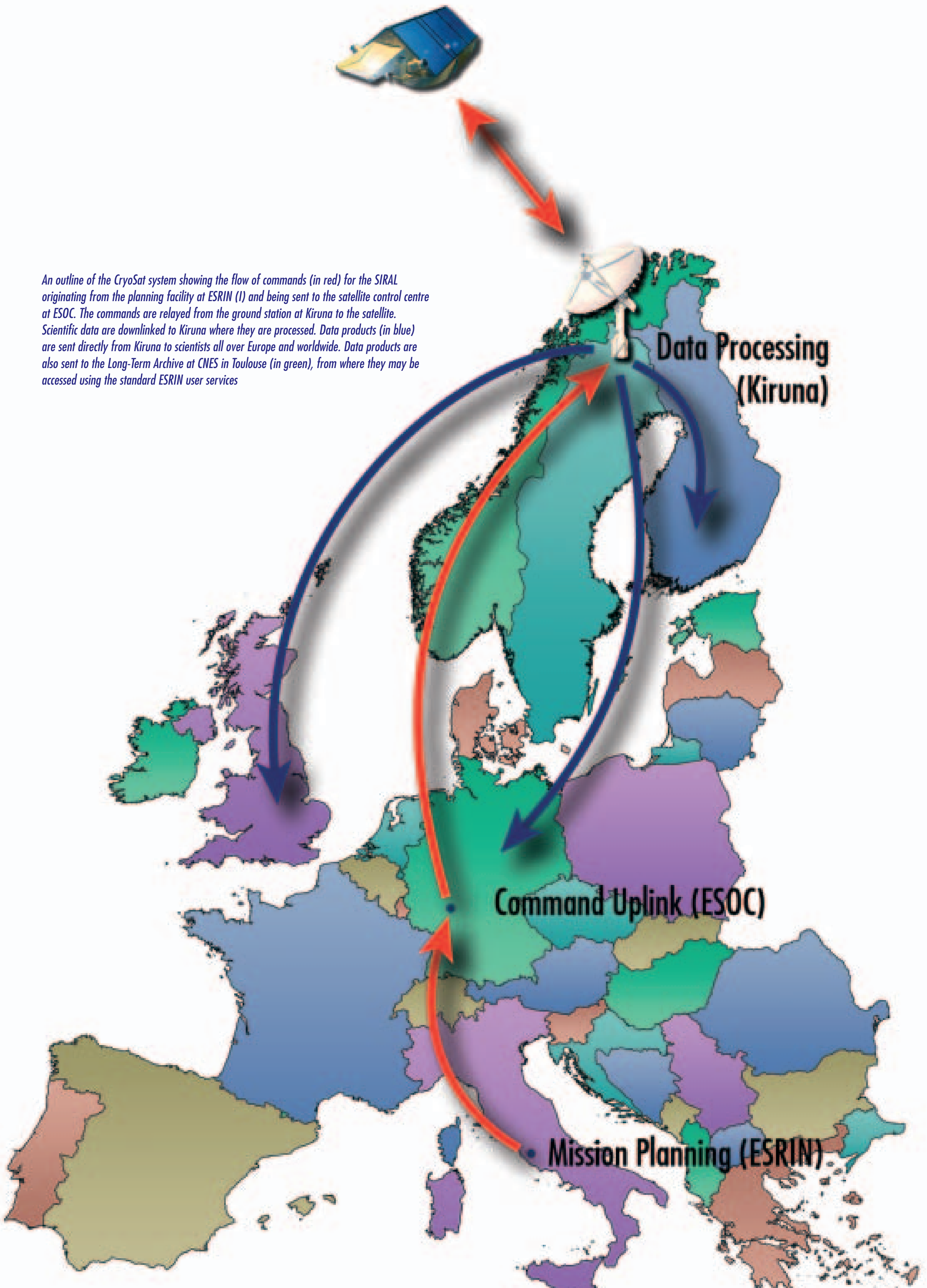

An outline of the CryoSat system showing the flow of commands (in red) for the SIRAL originating from the planning facility at ESRIN (I) and being sent to the satellite control centre at ESOC. The commands are relayed from the ground station at Kiruna to the satellite. Scientific data are downlinked to Kiruna where they are processed. Data products (in blue) are sent directly from Kiruna to scientists all over Europe and worldwide. Data products are also sent to the Long-Term Archive at CNES in Toulouse (in green), from where they may be accessed using the standard ESRIN user services

The CryoSat Data Products:

– Their generation, in-situ validation and applications

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The preceding articles have described how the CryoSat mission came about, how it was designed, and how the satellite was put together. Little has yet been said about how we will plan the operations, or about the data that will flow to the scientific community. This last article therefore describes those parts of the overall system that will not be launched into space. They include the control and processing centres, as well as less material things like the operations concept and the approach to validation

CryoSat was conceived with clear ideas about the scientific potential of the measurements it would produce. Now, shortly before launch, we have accepted 80 proposals from scientific groups who want to exploit this potential, and this article concludes with some examples.

System Architecture

In the previous articles, the main reference to the ground segment was in terms of constraints on the satellite design, stemming from the decision to use a single ground station. However, there is much more to be said about the ground activities; indeed once the satellite is in orbit the ground facilities, operations and planning, and ultimately the resulting data products, are the only tangible part of the mission.

Conceptually the system architecture is simple, which is largely a consequence of the clear focus of the mission. This has meant that the operations planning can be agreed with the users well in advance, with little need for special planning to meet unexpected user requests.

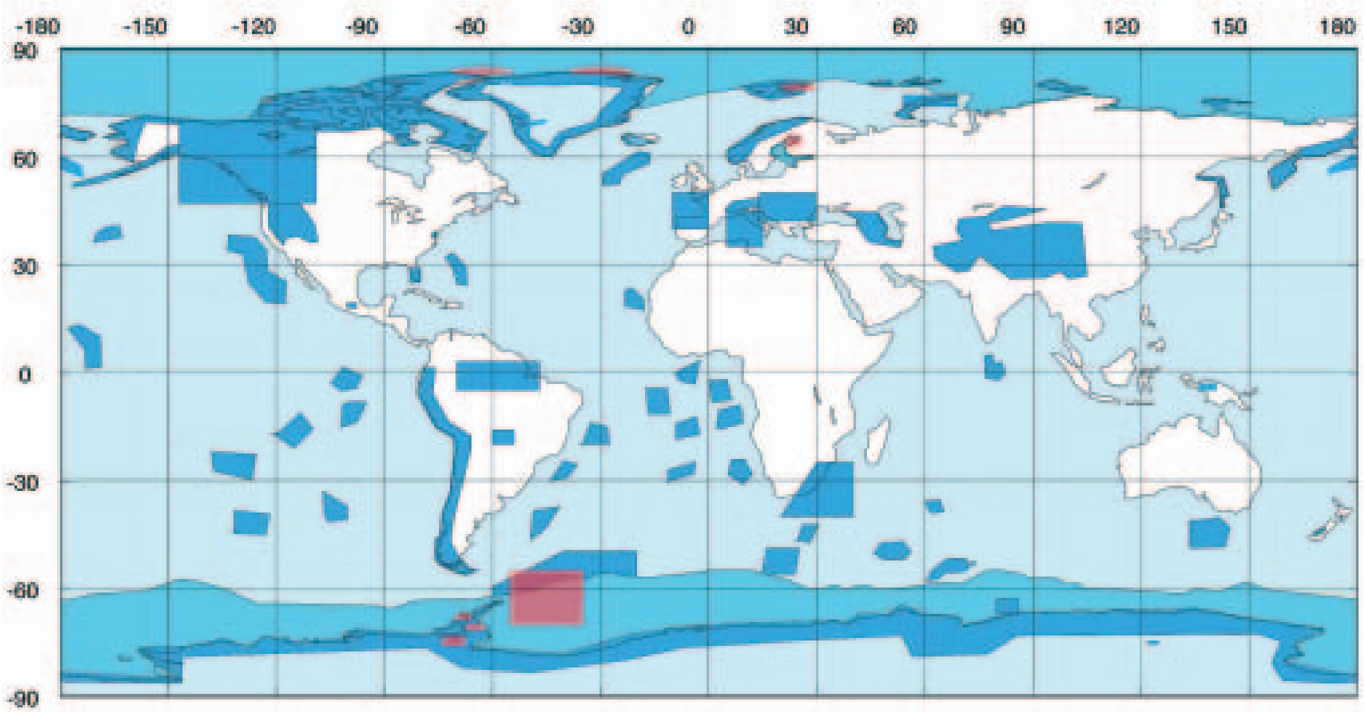
The main parts of the system are the planning facility at ESRIN (I), the Mission Control Centre at ESOC (D), and the ground station at Kiruna (S). As well as providing the link to the satellite, the Kiruna station hosts the data processing and archiving system. From here, the scientific data will be distributed directly to users.

There are other data flows in the system since CryoSat, like any altimeter mission, needs auxiliary data from a variety of sources. For example, the precise orbits are computed by an expert group at CNES in Toulouse (F). They need to get the data from the DORIS instrument as soon as it is available, and will take 30 days to compute and check the orbits to the highest accuracy (the 30-day delay is not important for the CryoSat mission). These data will be sent back to Kiruna and incorporated into the CryoSat data products.

The number of these internal interfaces can make the full system appear complex, but they are simple data transfers, which are extensively tested before launch. To the scientist using CryoSat data the system will appear extremely simple: it is an FTP server.

Planning the Operations

Unlike the previous ESA Earth-observation missions, the planning of CryoSat operations is very static, and this is quite appropriate for what is essentially



These are the geographic zones used for planning SIRAL operations. The pale-blue regions are where the conventional Low Rate Mode will be used, the intermediate-blue regions are for SAR and the darker-blue ones for SARIn. The red areas are identified calibration and validation areas

a survey mission. The key to this is that the exploitation of the three different measurement modes of the SIRAL instrument can be planned well in advance.

The original CryoSat concept proposed by Prof. Wingham already identified geographic zones where the various SIRAL modes would be used; for example, the mountainous edges of the ice caps and glaciated regions of the World were delineated on a map and marked for SARIn mode. These zones have become the definition of the baseline mission.

Following the two Announcements of Opportunity (AOs) that were issued, many scientists have defined further regions that they want to study using specific SIRAL modes. These have been added to the map defining the baseline mission, along with some specific regions that will be used for calibration and validation measurements. The resulting patchwork of zones forms the heart of the mission-planning system.

In fact, twelve such maps have now been defined, one for each calendar month, taking account of the seasonal variation in sea-ice cover in both hemispheres. The example shown here corresponds to September.

Now that we have distilled the users' data needs into these maps, the planning cycle can become quite automated. By planning we mean the generation of a time sequence of commands to the payload, each with an associated time when it must be executed – this is called the 'mission timeline'. It is prepared by overlaying the ground-tracks of the orbit, calculated in advance for the relevant period, over our map and determining the times at which the mode transition commands must be executed as CryoSat passes from each zone to the next. Needless to say, this is done by software, and extra functions for checking the flow in and out of the onboard data recorder are implemented too.

In keeping with the programmatic constraints, all of the nominal activities occur during normal office hours and so planning is done on a weekly basis, starting three weeks in advance. The sequence of activities will go like this:

- during week *n-2*, the operation timeline for week n will be generated at ESRIN and sent to ESOC
- during week *n-1*, ESOC will upload the timeline of commands to the satellite and store them onboard
- commands will be executed onboard during week *n*, but
- up to 4 working hours before their execution, last-minute commands (for special calibration targets) can be planned by ESOC and added to the onboard timeline.

What is notable about this cycle is that the information flows are unidirectional: commands to the satellite and data products to the user.

So What are the Data Products?

In the previous article, we have described the prodigious amounts of data generated by CryoSat, namely some 50 Gb per day. Modern desktop computers could perhaps swallow just a few days of this. At the ground station, this incoming 'stream' (perhaps 'torrent' would be more appropriate) of data is separated into files according to the payload instrument mode. These files are the so-called 'level 0' data products; they are archived at Kiruna, but not distributed.

The ESA Kiruna ground station, originally set up for ERS-1, had a second antenna added for Envisat. As well as supporting other ESA missions, it is the only ground station for the CryoSat mission and hosts the data-processing, local-archiving and distribution functions

The first step in making something meaningful from the data is to generate a product of the same size as the level 0, but now containing the coherent synthetic radar beams (achieved by applying a two-dimensional FFT to the bursts of radar echoes). This so-called 'full-bit-rate' product is also archived, but not generally distributed. The data volume and the complexity of applying the necessary calibration corrections makes this product attractive only to all a handful of very specialised radar laboratories.

A reduction in data volume, to about 4 Gb per day, occurs in the next step, whereby all of the synthetic radar beams illuminating a given strip of the Earth's surface are combined into one composite radar echo, a process we call 'multi-looking'. These echoes, which include phase information for the SARIn mode, have been calibrated and constitute the 'level 1b' products – one product type per instrument mode. Several CryoSat users plan to exploit these radar-echo data using their own customised re-tracking software, and so the level 1b products are available to registered users.

The final step in the data processing at Kiruna takes the level 1b products and applies specific re-tracking of power and phase to generate a product that can be used directly by geo-scientists rather than radar scientists. This 'level 2' product contains measurements of the surface elevation along the ground-track, corrected for the atmospheric and geophysical effects which always have to be taken into account in altimetry. The product has a space reserved for sea-ice thickness, but this parameter will not be calculated at the start of the mission since we are not confident in all aspects of its computation until more in-situ measurements have been made, as we will describe later. Until that time the space will be used for the ice freeboard measurement.

This level 2 product is packaged as a single file per orbit and the data are substantially refined compared to the lower-level products: at 50 Mb, a full day's worth of data could be downloaded in 10 minutes over a slow 1 Mbps ADSL connection, and the entire mission could be stored on an iPod.

These level 2 data are only generated and distributed when the precise orbit becomes available from CNES, which takes 30 days. So to satisfy the existing meteo-ocean community who require a subset of altimeter data in near real time, which is to say within 3 h of the measurement, there is a further dedicated product. This so-called 'FDMAR' product (named for commonality with a similar Envisat product) is processed in the same way as the regular level 2 product, but uses the real-time orbit solution computed by DORIS and normally used for onboard satellite control. Its main content is ocean elevation, wind speed and wave height, and it is only made from the SIRAL low-rate-mode data over the oceans.

The CryoSat system was not designed for such operational purposes, however, and this product has only recently been introduced. Clearly, it can only be generated on a 'best effort' basis and will not always be available. For example the 3–4 blind orbits each day will not be available in near-real-time. Despite such caveats, the fact that it has been possible to introduce, at a late stage, such a radical feature as systematic near-real-time processing and distribution is a credit to the conceptual design of the CryoSat data-processing system.

How the System Works

The data-processing system is also named after an equivalent Envisat function, namely the PDS or Payload Data Segment, and it is the entity that is connected to the radio-frequency equipment of the receiving antenna at one end, and provides data products to users at the other. Much of what the PDS does is data management and cataloguing. The heavy-duty number-crunching and complex software is isolated to a specific part called the instrument processing facility, or IPF, which is embedded in the PDS.

The IPF, like most of the PDS, is actually implemented as a cluster of high-performance dual-processor PCs running Linux. The operation of the PDS is data-driven, which is to say that it is controlled by the presence and nature of unprocessed data, rather than by external commanding. It is an automaton. The arrival of a signal at the demodulators at the front end triggers the level 0 processor to extract and archive the level 0 products. It also writes their details to a database.

A central control function that watches this database notes their arrival and checks what type of files they are. For each type of file, it knows what has to be done – it has a list. It puts together a job order that identifies the type of processor which must be run on it (SIRAL low-rate-mode data is processed differently from star-tracker data, for example) and the auxiliary data that will be needed. These auxiliary data files may include atmospheric-correction data and precise orbit determination, for example, and the relevant time coverage needed is also noted in the job order.

When any member of the IPF cluster is not busy, it will pick up a job order and, if it specifies a processing task it can do, it will check the database to see if all the needed auxiliary files are there. For newly generated job orders they will not normally be, so another one is checked until it finds one where all of the pre-requisites of the particular job order are satisfied. Then the processor gets on with its job and eventually stores the results into the archive, informing the PDS controller via the central database.

This concept applies to all the product levels. The PDS controller also has a list of all the CryoSat users and what data products they are registered for. For each new product appearing in the database, it goes through its user list and puts a copy of the new product file in the local FTP directory of each relevant user. For voluminous data products (e.g. full bit rate), it prepares physical media such as burning a DVD.

From this description, it is clear that the operation of the CryoSat data processing system is actually configured by a set of lists that define what has to be done. There are no commands and little operator intervention, except for physical media handling.

Despite the rigidity of the operations flow, the system provides flexibility by, for example, allowing the addition of a new type of processing algorithm and more entries in the configuration lists. This is how the new FDMAR capability is being added. Even specific activities like calibration, which also require rapid data access, are handled in the same way.

As we noted earlier, this system is characterised by a one-way flow of data from the satellite to the users. There is no dynamic feedback/request loop, with users systematically involved in the planning process.

How *do* Users Interact?

The only way in which scientists can become users of CryoSat data is via the Announcement of Opportunity (AO) process. ESA's Earth-observation missions are supported by two AO mechanisms: an infrequent formal AO, and a continuous 'Category 1', or Cat1, mechanism. This latter name is meaningless unless one is familiar with the categorisation of data users agreed between ESA and the member states. What it means however is that scientists may make proposals to a rolling AO process, with the only drawback, compared to a formal AO, that if accepted they have to pay data reproduction costs. However, with CryoSat's principally electronic transfers this distinction is academic.

There have been two AOs for CryoSat and 80 proposals have been accepted. Many of the proposals will exploit data from CryoSat's baseline mission, but others led to an extension of the geographical masks as we described earlier. In all cases though, with the acceptance of his/her proposal the Principal Investigator (PI) has been registered to receive the data products that they need. Again we should emphasise that this is a static configuration of the user needs into the planning, processing and distribution system.

For new Cat1 users, a similar procedure will apply. Any changes that users wish to introduce will also follow the same route and lead to a change in the static configuration.

We have already explained that it is intended to distribute CryoSat data to most users by electronic means. Possible exceptions to this are the level 1b and full-bit-rate users, where the volume of the data may make this prohibitive. Tests are underway which should reveal, by mid-2005, if the level 1b data can be distributed by FTP, but it appears likely that the few users who need full-bit-rate data will be receiving them on physical media.

As with previous missions, the data products will not be made fully available to users until after the commissioning phase, which we expect to last 6 months. Principal Investigators who are participating in the calibration and validation activities will receive unvalidated data earlier.

The Approach to Product Validation

The validation of the CryoSat data products is essential if all the hard work in building up the rest of the system is to be fully exploited. In his earlier article Prof. Wingham identified that the residual uncertainty in the determination of ice thickness trends should be "… no more than 10% greater than the limit of natural variability".

There are two contributing factors to this residual uncertainty. The first source is the imperfections of the measurement system itself. These have been addressed during the mission and equipment design, and

Drilling cores into the ice sheet to measure fluctuations in snow fall and near-surface density

The locations of the main CryoSat validation sites in the Arctic

now that the satellite is under final testing their contribution to the overall uncertainty is relatively well known.

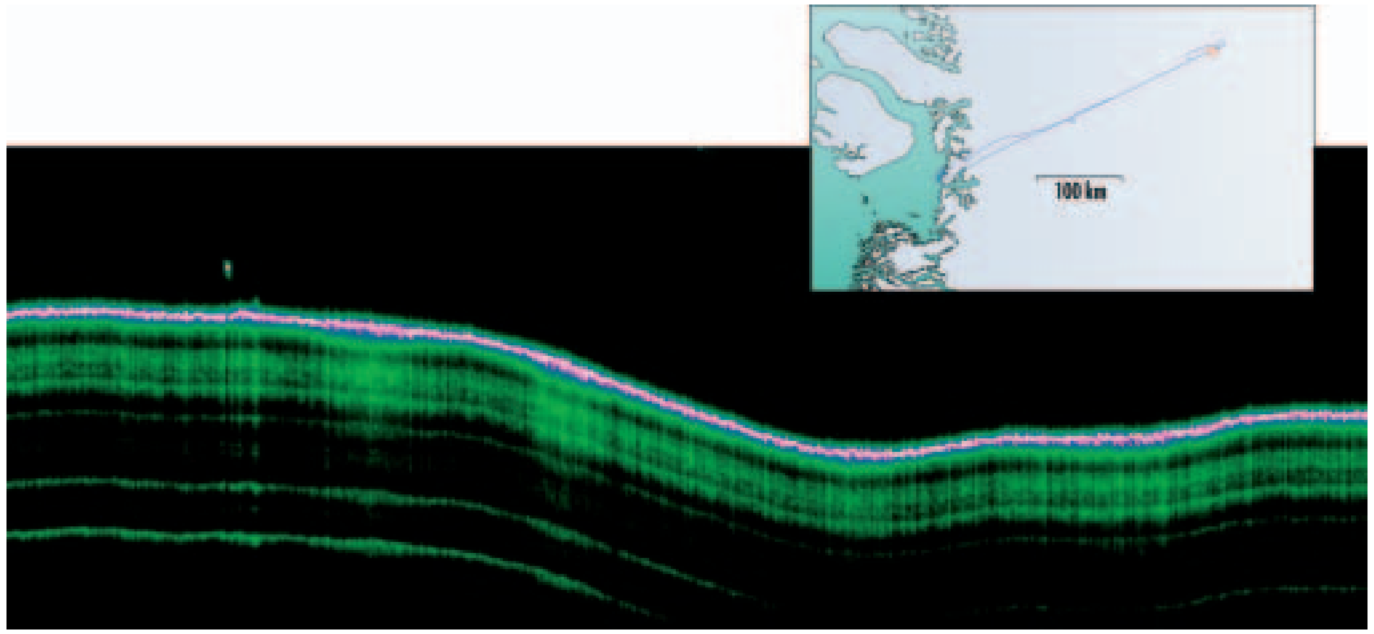
The second and more troublesome source are the geophysical uncertainties affecting the transformation of level 1b products (which are essentially radar-echo delay-time measurements) into level 2 products, containing parameters such as surface elevation or ice thickness. The uncertainties stem from the complexity and changing nature of natural ice surfaces. For land ice, the main sources of error include uncertainties in snowfall fluctuations and near-surface density required for mass-balance calculations and the variable penetration of the CryoSat signal into the snow cover as snow conditions change with location and time of year. For sea ice, variable penetration of the signal into the snow covering the ice is also a source of error. Additional errors arise from the weight of snow on the ice (which reduces the freeboard measured by the radar), preferential sampling by CryoSat of the larger ice floes, as well as lack of knowledge about ice-density statistics.

Validation is the process by which we will quantify the overall uncertainties in the ice trends that will be derived from the CryoSat data. In practice though, as the measurement-system contribution is relatively well understood, this really means the quantification of the uncertainties in the CryoSat products. Recognising that this would inevitably mean the collection of independent measurements of the quantities in the CryoSat data products, and that such measurements would require venturing into cold and hostile conditions, we sought the help of experts – the polar scientists who routinely collect such data.

The main mechanism for this was the first CryoSat AO, which focused exclusively on calibration, validation and consequent improvement in the CryoSat data processors. As a direct result, we set up the CryoSat Calibration, Validation and Retrieval Team (CVRT) and together have elaborated a comprehensive validation programme. Derived from a detailed breakdown of the problem, this programme includes a coordinated strategy and a plan for a series of field experiments. The validation implementation plan that we have evolved defines a series of experiments over the period 2003–2007.

The principal means for carrying out independent measurements for validation is through dedicated independent, ground-based and airborne campaigns, along with detailed investigations of retrieval methods applied to the satellite measurements.

The AWI Dornier 228 aircraft carrying the ESA radar altimeter ASIRAS along with a laser altimeter. This aircraft was used for 2004 pre-launch validation experiments focused mainly on land-ice validation



Radar-echo data from the ASIRAS instrument, collected on 14 September 2004 over one of the validation sites on the EGIG line in Greenland. The plot shows about 3.5 km of ground track laid out along the horizontal axis. The vertical axis represents range from the radar and is colour-coded according to the power of the echo. The span of ranges in the plot covers just over 22 m, with a resolution of 8.7 cm, substantially better than SIRAL. The radar wave clearly penetrates the surface, showing a strong return near the surface (white) and several subsurface layers in green. The radar flew over a corner reflector mounted 2 m above the ground (marked on the map by a star) and this echo can be seen as a 'blip' about 20% of the way along the track

There are three key elements in the validation plan:

Repeated experiments

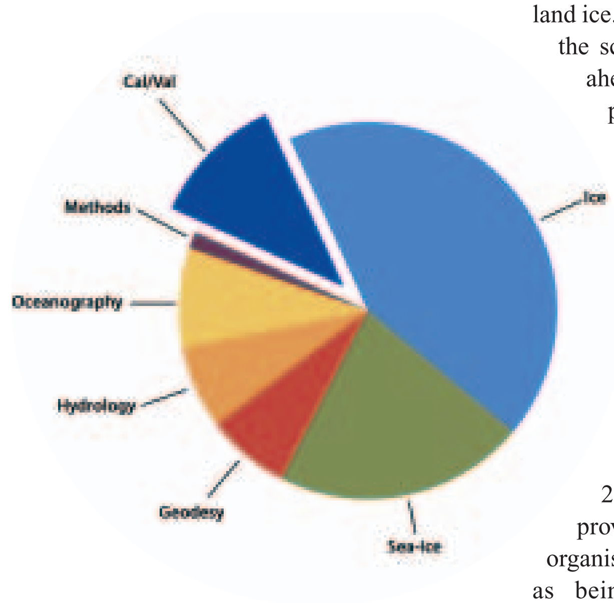
Errors due to the variable penetration of the CryoSat radar signal into the snow cover can only be addressed through repeated experiments, at different times during the annual cycle, to capture the effect of different snow conditions. The preferred dates for the experiments are in Spring and Autumn, which represent the maximum and minimum snow depth during the seasonal cycle.

Co-ordinated ground and aircraft experiments

CryoSat traces its ground track at high speed – over 6 km/s – and covers the polar regions very quickly. As the ice properties vary on a whole range of spatial scales, it is not reasonable to compare individual ground measurements, made at just a few sites on the ice, directly with CryoSat. The solution is to make measurements with systems that encompass all the spatial scales, and to establish traceability from one to the other. This principle is applied to both land ice and sea ice, though the details of the measurements may differ slightly. We shall take sea ice as an example.

Direct measurements of ice thickness are made in-situ by drilling boreholes in the ice. At very local scales this is a direct measurement, which can be extended to larger scales by using an electromagnetic sensor hung beneath a helicopter as it flies low over the ice. The helicopter's range is limited and its speed is relatively low, so both range and speed are increased by using an aircraft. This also involves a change of sensor: the aircraft carries a scanning laser altimeter and a radar altimeter with the same operating principle as SIRAL. The ASIRAS airborne radar, developed by ESA, is used for this. With the range and speed of the aircraft, we have the possibility to bridge the gap to the satellite scales.

Logistics in the difficult Arctic environment are one of the main challenges of the CryoSat validation experiments. This is the camp on Canada's Devon Island where scientists making the ground measurements stayed for up to 4 weeks



Distribution of the 61 accepted proposals received in response to the Data Announcement of Opportunity (AO). A further 19 Cal/Val proposals were accepted for the Cal/Val AO

Such experiments require careful coordination between all activities, to ensure overlap between ground, helicopter, airborne and satellite coverage of the ice, particularly if, like sea ice, it is moving.

Pre-launch validation activities

Several of the CryoSat validation experiments, in particular those requiring co-ordinated ground and aircraft experiments, have never been carried out before. Pre-launch trials have therefore been critical in order to validate the experimental concept and get a head start in addressing the validation objectives.

Since 2003, we have carried out several major validation experiments with polar scientists from the UK, Germany, Norway, Finland, Denmark, Canada and the USA. In a typical experiment, the airborne team flies up to 10 000 km over Arctic sea and land ice. The airborne data acquisition over the scientists on the ice is coordinated ahead of time through a series of planning meetings, and then via satellite phone during the experiment itself. The airborne acquisition campaign lasts about two weeks, whereas some of the surface teams have spent up to three months on the ice-cap making in-situ measurements of ice conditions to be compared later with the airborne radar.

Initial results from the 2003–2004 experiments have provided valuable feedback on the organisation of future campaigns, as well as being scientifically interesting in themselves. In particular, one of the objectives of the activities in 2003 was to demonstrate that measurements from platforms moving at substantially different speeds (helicopter, aircraft and satellite) could make measurements at the same place on sea ice floes moving in the ocean currents, and do it reliably over long distances. This experiment, which involved estimating the ice movement and flying along compensated headings, had not been attempted before and its success was vital to the validation approach that we have adopted.

After the CryoSat launch, the subsequent validation activities will be used to assess more directly the retrieval errors in the CryoSat products, through comparison with the airborne data. The understanding of the uncertainties in the CryoSat measurements will enable the full and proper exploitation of the data products.

Applications of CryoSat Data

As mentioned earlier, the two CryoSat AOs have resulted in 80 accepted proposals from scientific groups all over the World. While many of these groups intend to exploit CryoSat data for research into the fundamental questions of large-scale cryospheric mass-balance which originally prompted the CryoSat mission, others plan to use the data for more localised research. Some of these projects partially overlap the original primary goals of the mission, such as detailed surveys of Antarctic drainage basins, and others, studies of European glaciers for example, represent applications that were also foreseen and included in the planning of the baseline mission.

Indeed, all of the ice-covered regions of the Earth were included for SARIn coverage, and such detailed but localised research into glaciers has been accommodated with no extension of the baseline mission needed.

A further set of applications involve the exploitation of the SAR or SARIn mode over surfaces that were not included in the baseline mission. This can be seen in the map of the geographic mode switching mask, which we showed earlier. These applications intend to explore the potential of the much higher along-track spatial resolution of the SIRAL for investigations into hydrology and fine-scale marine geodesy and bathymetry, for example. The need for improvements in detailed bathymetry on a global scale was brought home by the serious collision of a US nuclear submarine with an uncharted sea-mount on 7 January 2005.

Finally, in addition to the 80 accepted AO proposals, we now have an additional user community joining the CryoSat team, with the introduction of the FDMAR near-real-time ocean product. This community includes up to 50 operational entities, such as meteorological services.

The CryoSat mission will provide useful information to such vital services; it will show the way in the development of satellites for high-resolution global measurement of ocean topography and bathymetry; it will provide a high-precision data set, which can be used to further study the on-going shrinking of temperate glaciers, and finally it will substantially reduce our uncertainty in answering one of the major questions of our time, namely: Are the ice masses of the cryosphere in retreat, and if so how long do we have before this starts to have a fundamental impact on human society? esa