The CryoSat System
– The satellite and its radar altimeter

In the preceding article Prof. Duncan Wingham has outlined the genesis of CryoSat, its scientific objectives and its programmatic constraints. The mission objectives are characterised by the determination of small height-related changes over a three-year period. This imposes requirements on the type of measurements to be made, the physical stability of the system, control of the measurement configuration, and consistency in the data-processing system. The programmatic constraints, on the other hand, may be simply characterised as the need for a relatively short development cycle with a stringent cost ceiling.

CryoSat is a fully integrated system in which all of the elements have been developed together within the programme to ensure the control needed to satisfy the mission objectives. However, in the interests of readability, the system’s description has been split over two articles: this one describing the elements that are to be launched into space, and the following one those parts that will remain on Earth.

Precision Measurements from Space

The CryoSat satellite is the part of the system that makes the measurements. The fundamental measure is the distance from the satellite to the Earth’s surface below, and for this a radar altimeter is used. Given the enormous success of the ERS radar altimeters over icy surfaces, this was a natural choice. CryoSat’s radar altimeter is called SIRAL, a contraction of SAR (Synthetic Aperture Radar) and Interferometric Radar.
The full CryoSat system has several parts, and although we will not describe here those that will remain on the ground, we will outline the overall architecture as this has an impact on the design of all of the elements. Programmatic constraints were dominant in this part of the system definition and led to the minimum configuration required to satisfy the mission objectives. The key feature is that a single ground station is used for CryoSat, both for command and control and for downlinking, processing and distribution of the science data. The ESA ground station at Kiruna in Sweden was selected. As well as enabling the sharing of resources with other on-going ESA missions, this choice resulted in manageable requirements in terms of handling the 3 to 4 consecutive orbits per day during which contact with the ground station is not possible.

The design of the CryoSat satellite was determined, as is always the case, by a number of key factors. From the mission-science objectives came the payload complement and its requirements, the orbit and the minimum lifetime. Programmatic constraints included the need to operate from a single ground station, launch on a ‘small’ and therefore low-cost launcher, extensive onboard autonomy, a low-cost design and a decision to forego the normal approach of building pressureless, ‘proof-of-concept’ models of the satellite (structural model, engineering model, etc.).

While it is not the case that these driving factors led inevitably to the CryoSat design (indeed during the competitive feasibility-study phase, another entirely different concept was developed), it is true that the main features of CryoSat can be traced back to these drivers. A major role was also played by heritage from the CHAMP and GRACE satellites, which were designed against similar orbital and programmatic constraints.

So instead of a rather ponderous deduction from the scientific requirements, here we will take a reverse engineering’ look at CryoSat to show how it responds to these drivers. We will start with the most obvious feature, its shape. So why does CryoSat look like dog kennel?

As mentioned earlier, the required orbit is not Sun-synchronous. Every day the orbital plane shifts to almost 3 minutes earlier with respect to the Sun; in 8 months, therefore, it drifts through all local times. This means that the direction from which sunlight falls on the satellite is constantly changing. The operation of the SIRAL instrument demands that its antenna points towards the Earth’s surface, which means that rotating the satellite to face the Sun is out of the question. Mechanisms on satellites are very costly and so the

Cryosat System

CryoSat geometry was arranged such that every orbit has enough sunlight on one or both of the solar panels to maintain a positive energy balance onboard. This assumes, of course, that the solar panels have the intrinsic capability to generate enough power to power the spacecraft, if the Sun were shining directly on them. The requirement to fit CryoSat inside the fairing of a ‘small’ launcher put absolute constraints on the size of the panels, thus removing one of the key degrees of freedom in this equation. That only left one parameter to ensure sufficient power generation – the efficiency of the solar cells themselves. Thus CryoSat, as a low-cost mission, has ended up pioneering the use of new, high-efficiency solar cells in low Earth orbit. More about this later, but we can say right now that this choice was still cheaper than integrating folding-out solar panels.

The two SIRAL antennas are accommodated side-by-side near the front of the satellite. They are slightly elliptical in outline in order to fit within the launcher’s fairing – which slightly complicates the scientific data processing, but has no impact on performance. We have already indicated that both the structural stability and the low Earth orbit. More about this later, but we can say right now that this choice was still cheaper than integrating folding-out solar panels.

The two SIRAL antennas are accommodated side-by-side near the front of the satellite. They are slightly elliptical in outline in order to fit within the launcher’s fairing – which slightly complicates the scientific data processing, but has no impact on performance. We have already indicated that both the structural stability and the low Earth orbit. More about this later, but we can say right now that this choice was still cheaper than integrating folding-out solar panels.
Like all of CryoSat’s equipment, the SIRAL radar altimeter is derived from existing equipment, in this case a conventional pulse-width-limited altimeter called Poseidon-2, which is currently flying on the US-French Jason mission. SIRAL is a single-frequency Ku-band radar, featuring some new design characteristics that enable it to provide data that can be more elaborately processed on the ground (a high pulse-repetition frequency and pulse-to-pulse phase coherence are needed for the along-track SAR processing). The across-track interferometry needs a second complete receiver chain, including the second antenna. These features make this instrument unique.

The electronics of the radar are divided into a number of separate units, principally for ease of manufacture and testing. One large unit houses all the digital electronics, and the remaining boxes contain radio-frequency circuitry and the transmitter’s power supply. Several innovations were necessary compared to the Poseidon-2 equipment, most notably due to the need for significantly increased transmitter power, which led to the development of a complete new transmitter section, and in the provision of the second receive path.

We have already mentioned SIRAL’s ability to operate in different modes. The low-resolution mode operates in the same way as a conventional pulse-width-limited altimeter and uses a single receive channel. The rate at which the radar pulses are transmitted is low, relatively speaking, at 1970 per second, and the echoes are transformed from the time domain to the spectral domain and averaged onboard. The data rate at which scence data are generated in this mode is therefore low, at 51 kbps. This mode will be used over ice sheet interiors, where the surface slopes are small. It will also be used over the ocean.

In the SAR mode, which also uses a single receive channel, the along-track horizontal resolution of the altimeter is improved during the on-ground processing by exploiting the Doppler properties of the echoes. The result is equivalent to decomposing the main antenna beam into a set of 64 narrower synthetic beams along-track. The footprints of the different sub-beams are overlapped, and flat surface are adjacent rectangular areas ~250m wide along-track, and as large as the antenna footprint across-track (up to 15 km). Consequently, a larger number of independent measurements are available over a given area, and this property is used to enhance the accuracy of the measurements over sea ice. To ensure coherence between the echoes from successive pulses, the pulse repetition frequency is about 10 times higher than for the low-resolution mode. The instrument operates in bursts, with a group of 64 pulses transmitted together, followed by a pause during which the echoes arrive. The echoes are then stored onboard in the time domain, without any averaging. Therefore, the data rate is significantly higher, at 11.3 Mbps. The SAR-Interferometric mode (SARIn) is used mainly over the ice-sheet margins, where the surface slopes are high. The combination of SAR and interferometry makes it possible to accurately determine the arrival direction of the echoes both along and across the satellite track, by comparing the phase of one receive channel with the other. In this mode, both receive channels are active and the corresponding echoes are stored over the time domain. The data rate is about twice as high as for the normal SAR mode. In order to cope with abrupt height variations, the range-tracking concept for this mode has to be particularly robust. In SIRAL, this is ensured by using narrow-band tracking pulses, transmitted between successive wideband measurement bursts.

Cryosat’s DORIS receiver is part of an overall system that is able to provide orbit tracking measurements and time-transfer. The DORIS system consists of a network of more than 50 ground beacons, receivers on several satellites in orbit, and ground-segment facilities. It is part of the International DORIS Service (IDS), which also offers the possibility of precise location of sea-beacons.

Each beacon in the ground network broadcasts two ultra-stable frequencies (at 2036.25 and 401.25 MHz). The use of two frequencies allows the ionospheric effects to be compensated for. Every 10 seconds, the onboard receiver measures the Doppler shift of these signals using an ultra-stable oscillator as a reference; this essentially enables the line-of-sight velocity to be determined. The set of radial velocities from the dense network of precisely located beacons forms a rich set of tracking data. The full set of DORIS measurements are processed with a lengthy quality-control and checking process within the ground segment (at CNES, as explained in the following article) before a final, high-precision orbit determination is performed: this is the stable reference needed to extract the most subtle signals from the SIRAL measurements.

The DORIS system includes the

Key characteristics of the SIRAL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LRM</th>
<th>SAR</th>
<th>SAR-In</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length</td>
<td>48.8 μs</td>
<td>48.8 μs</td>
<td>48.8 μs</td>
</tr>
<tr>
<td>Burst length</td>
<td>3.6 ms</td>
<td>3.6 ms</td>
<td>3.6 ms</td>
</tr>
<tr>
<td>Pulses per burst</td>
<td>64</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Burst repetition interval</td>
<td>11.7 ms</td>
<td>11.7 ms</td>
<td>46.7 ms</td>
</tr>
<tr>
<td>Azimuth looks (46.7 ms)</td>
<td>91</td>
<td>91</td>
<td>60</td>
</tr>
<tr>
<td>Tracking baud width</td>
<td>350 MHz</td>
<td>350 MHz</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Sample rate</td>
<td>0.47 m</td>
<td>0.47 m</td>
<td>3.75 m</td>
</tr>
<tr>
<td>Size of tracking window</td>
<td>60 m</td>
<td>60 m</td>
<td>480 m</td>
</tr>
<tr>
<td>Averaged tracking pulse (46.7 ms)</td>
<td>92</td>
<td>92</td>
<td>24</td>
</tr>
<tr>
<td>Data rate</td>
<td>11.3 Mbps</td>
<td>11.3 Mbps</td>
<td>11.3 Mbps</td>
</tr>
<tr>
<td>Power consumption</td>
<td>125.5 W</td>
<td>125.5 W</td>
<td>123.5 W</td>
</tr>
</tbody>
</table>

The SIRAL electronics equipment essential in the ice of the satellite

The Payload: Re-use and innovation

The majority of the satellite is made of aluminium, and so another vital characteristic that enables it to provide data is small. It will also be used over the

introduction of some special means of calibrating phase performance in flight.

The antenna subsystem has not been immune to this. It was developed as a discrete item consisting of two Cassegrain antennas mounted side-by-side on the rigid antenna brench. The two antennas are identical, but one is used both to transmit and receive, whereas the other is used only to receive echoes. The Cassegrain design offers particular advantages for the SIRAL as the resulting waveguide lengths are much shorter than those required for the more common, front-end design. The entire assembly went through a measurement campaign that challenged the capabilities of the hot facility due to the exacting phase-measurement requirements.

CryoSat’s DORIS receiver is part of an overall system that is able to provide orbit tracking measurements and time-transfer. The DORIS system consists of a network of more than 50 ground beacons, receivers on several satellites in orbit, and ground-segment facilities. It is part of the international DORIS Service (IDS), which also offers the possibility of precise location of sea-beacons.
CryoSat in a Nutshell

CryoSat Mission
To determine fluctuations in the mass of the Earth's major land and marine ice fields.

Mission Duration
Six months of commissioning followed by a three-year operational mission.

Payload
SIRAL (Interferometric Radar Altimeter)

• Low-Resolution Mode provides conventional pulse-width-limited altimetry over central ice caps and oceans.
• SAR Mode improves along-track resolution (~250 m) over sea ice through a significantly increased pulse-repetition frequency and complex ground processing.
• SAR, Interferometric Mode adds a second receive chain to measure the cross-track angle of arrival of the echo over topographic surfaces at the margins of ice caps.

Star Trackers (3) measure the interferometric baseline orientation, as well as driving satellite attitude control. DORIS enables precise orbit determination, as well as providing in-orbit position to the AOCs.

Laser Reradiometer enables tracking by ground-based lasers.

Configuration
• Simplified rigid structure with no moving parts.
• All electronics mounted on nadir radiator.
• SIRAL electronics mounted close to antennas.

Dimensions
4.60 m x 2.34 m x 2.20 m

Mass
670 kg (including 36 kg of fuel).

CryoSat System

Power
• 25 kWe body-mounted solar arrays, with 800 W each at normal solar incidence.
• 60 Ah Li-ion battery.

Propulsion
• 2 x 40 mN cold-gas thrusters.
• Gas-turbine-nitrogen propellant (36 kg at 250 bar).

Spacecraft Attitude
• Three-axis-stabilised local-normal pointing, yaw-stabilising, with 6° nose-down attitude.
• Star trackers, magnetometers, magnetotropers and 10 mN cold-gas thrusters.
• < 0.1° pointing error; < 0.001° stability.

Command and Control
Integrated data-handling and AOCs computer; communication by 1553 bus and serial links.

On-board Storage
• Solid-State Recorder, capacity 256 Gbits.
• Data generated onboard: 320 Gbit/day.
• Full mission operation with a single ground station at Kiruna.

RF Links
• S-band data downlink: 100 Mbps at 8.100 GHz.
• S-band TTC link: 2 kbps uplink, 8 kbps downlink.

Launch Vehicle
Rocket (converted SS-19), launch from Plesetsk.

Flight Operations
• Mission control from ESOC via Kiruna ground station.
• Onboard measurements automatically planned according to a geographically defined mask.

Payload Data Processing
• Data-processing facility at Kiruna ground station.
• Local archiving of data with precision processing after one month following delivery of precision orbits from DORIS ground segment.
• Possibility of quick-look data.
• User Services coordinated via ESRIN with dissemination of data from Kiruna.

esa Bulletin 122 - May 2005
www.esa.int

Cryosat System

possibility of encoding information on the uplinked signals, and two privileged master beacon stations at Toulouse and Kourou, provide such uplink services. Data uplinked from these stations (which is updated weekly and used by all DORIS instruments in orbit) include the coordinates of the stations, Earth-orientation parameters, etc. The uplinked data also include time signals that allow synchronisation of the DORIS internal time reference using the International Atomic Time (TAI) system.

These data are needed onboard because DORIS is able to make real-time orbit calculations from the data it collects, though with significantly less accuracy than the final precise orbit determination. However, this real-time orbit knowledge has expected errors of less than a metre and is used onboard by the central flight software to control the satellite's pointing (more on this later). Associated with this, DORIS also computes time, accurate to about 10 microseconds, which is also used onboard as the master clock. A final onboard service offered by DORIS is the provision of the reference frequency to the SIRAL instrument, which does not have its own ultra-stable oscillator. The frequency of the DORIS oscillator is continuously monitored as part of the precise-orbit-determination service, and this measurement is taken into account processing the SIRAL data.

CryoSat includes a set of three identical star trackers, which are the only means of determining the orientation of the SIRAL interferometric baseline. They are also the principal three-axis attitude measurement sensor in the nominal operating mode. They are lightweight, low-power-consuming, fully autonomous devices. They are accommodated such that the Sun and Moon can each blind only one head at any time; this makes the whole sensor system single-failure tolerant. The star-tracker algorithm is optimised to use a few faint stars, of around magnitude 5. Barely visible to the naked eye except at dark sites, they are far more numerous than the brighter stars and provide many more triangulation possibilities for the pattern-matching process in all directions of the sky.

The final element of the payload is the laser retroreflector, a passive optical device for ground-based measurement of the satellite's orbit by laser-ranging stations. Such reflectors are used on all radar-altimeter satellites, and several other spacecraft also. The device on CryoSat is based on an existing design that has been flown on many Russian and other satellites.

What Makes it Tick?

All of the data generated by CryoSat's scientific payload have to be recorded onboard as the satellite is only in contact with its single ground station for brief periods. Typically there are 10 passes of 5 to 10 minutes duration each day, occurring on consecutive orbits. These contacts are followed by a gap of 3 or 4 'blind orbits'. To handle the large data volume, a 256 Gbit data recorder is installed. Following the modern trend, this is realised as solid-state memory with literally thousands of RAM chips. The unit is derived from similar equipment on ESA's Mars Express spacecraft and, of course, comprehensive memory-management and data-handling functions are built in. It can continue recording data as it replays its memory into the data link to the ground station.

This downlink is a potential bottleneck because the total contact time is relatively short. To overcome this, the downlink data rate is especially high; at 100 Mbps, it is more than 12 times as fast as the best ADSL Internet access available in The Netherlands. Again this approach is built on heritage, this time from ESA's MarOp mission, with the frequency and bandwidth reused from an allocation originally given to EuroSat.

CryoSat is an unusual satellite in that it has virtually no moving parts, the only exceptions being a couple of valves in the propulsion system. This has led to savings in cost as well as testing. One area where this lack of moving parts is particularly noticeable is in the attitude and orbit control subsystem, where gyroscopes and reaction wheels are usually commonplace.

Attitude control for CryoSat is innovative since it principally exploits two of the payload equipment items, another example of re-use. The star tracker provides real-time measurements of the reference between a black and a mirrored surface on each face of the satellite, which together with the DORIS time and orbit information allows the onboard software to calculate the satellite's orientation with respect to Earth. Measurement is half of the problem; it is also necessary to produce torques that will turn the satellite as needed to keep it Earth-pointing within the required tolerance.

CryoSat's main means of generating such torques is to use electromagnets interacting with the Earth's magnetic field. The devices themselves, called 'magnetotorquers', are simply multiple turns of wire wrapped around a ferro core, powered by a controllable electric current from the main computer. Magnetotorquers cannot produce torque around the direction of the Earth's field itself, and this direction constantly changes with respect to the satellite. So a 'banking' control in the form of a set of small cold-gas thrusters guards against excessive pointing errors. These are very small indeed, with a thrust of 10 mN – about as much as the weight of 1 c.c. of water. Simulation has shown that these will need to fire for a total of about 3 seconds per orbit. Although this is not long, it will, together with the gas used by the 40 mN thrusters to maintain the orbit in the face of air-drag, eventually consume the 13 kg of pressurised nitrogen onboard.

The attitude-control system has other sensors too, which are used during periods of initial stabilisation after separation from the launcher, and in emergencies. These are a set of magnetometers and an ingenuous sensor, the combined Earth-Sun sensor, which measures the temperature difference between a black and a mirrored surface on each face of the satellite. A clever piece of software then calculates the direction to both the Sun and the Earth.

Putting it Together

One of the key means by which the CryoSat programme has been able to compress schedule and cost has been through a bold early programmatic decision. The idea was that by embracing existing equipment designs and building-

ESA Earth Observation

Kiruna ground station.

(3) measure the interferometric baseline

LEO, non-Sun-synchronous

369 days (30 day sub-cycle)

3.9

4/22/05 1:08 PM Page 8
in conservative margins, it would be possible to directly build a proto-flight satellite; no test articles would be built. The savings inherent in such an approach were very persuasive, in terms of both time and equipment. However, it was obvious that the benefit of test models, particularly the 'engineering model', goes beyond merely testing the hardware; they allow unglamorous but essential work, such as test-procedure debugging, to be done away from the critical path. So for CryoSat we decided to build a 'virtual satellite' in software. This has been so useful for various aspects of testing that it has already been cloned several times, a rather difficult feat to perform with a hardware version!

Nevertheless, by mid-2004 the proto-flight CryoSat was ready for final testing. The launch vehicle, called 'Rockot', is a converted SS-19 inter-continental ballistic missile, with a versatile, restartable upper stage known as Breeze-KM.

Getting it Up There
At the end of the test campaign, and after the Flight Acceptance Review, it will be time to ship the satellite to Russia for the launch. The launch site in Plesetsk, some 800 km north of Moscow. This very large facility has been used for Russian launches for many years, although is relatively new for European customers.

The launch will be towards the north, and the upper stage will shut down while over the Arctic. Then the composite of CryoSat attached to the upper stage will coast through about half an orbit before the Breeze-KM fires again, over South Africa. This final orbit-injection burn will put the composite into the correct orbit, and again it will coast until reaching Europe.

The launch time has been selected such that the orbital plane is at right angles to the direction to the Sun, so that the composite flies around the line marking dawn and dusk. This means that CryoSat is in sunlight all the time and can receive power from the solar arrays. A series of small burns by Breeze-KM keep CryoSat close to its nominal Earth-pointing attitude. All of these activities are performed blind, as the only communication with the launcher is from ground stations in Russia. The separation of CryoSat from the Breeze-KM after the final orbit-injection burn is therefore delayed until the composite comes within range both of the Russian stations and slightly thereafter the CryoSat ground station at Kiruna. Then, after almost a complete revolution, the final separation marking the start of CryoSat's autonomous life in orbit will occur somewhere over Romania.