The CryoSat System

– The satellite and its radar altimeter

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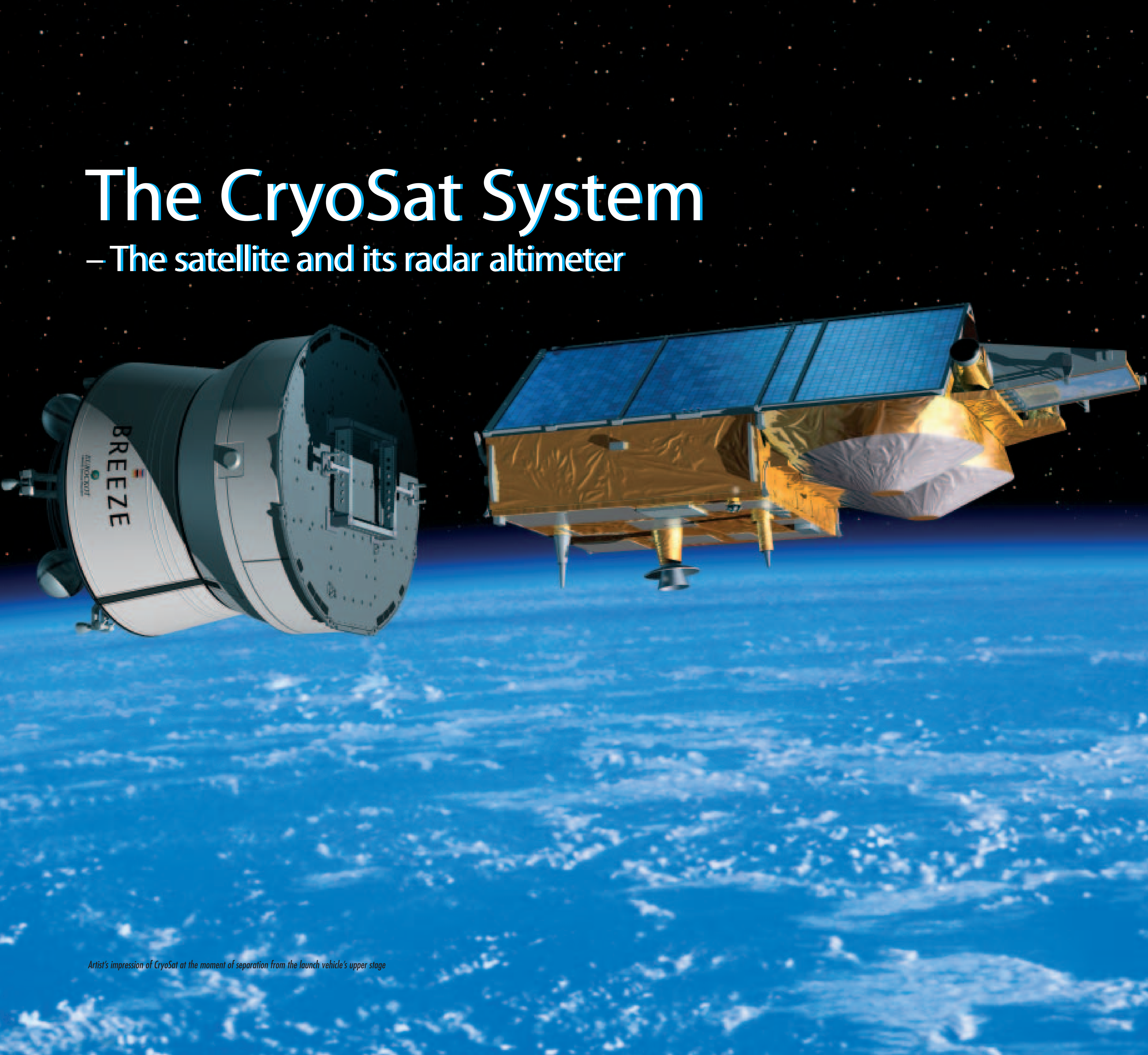


Artist's impression of CryoSat at the moment of separation from the launch vehicle's upper stage

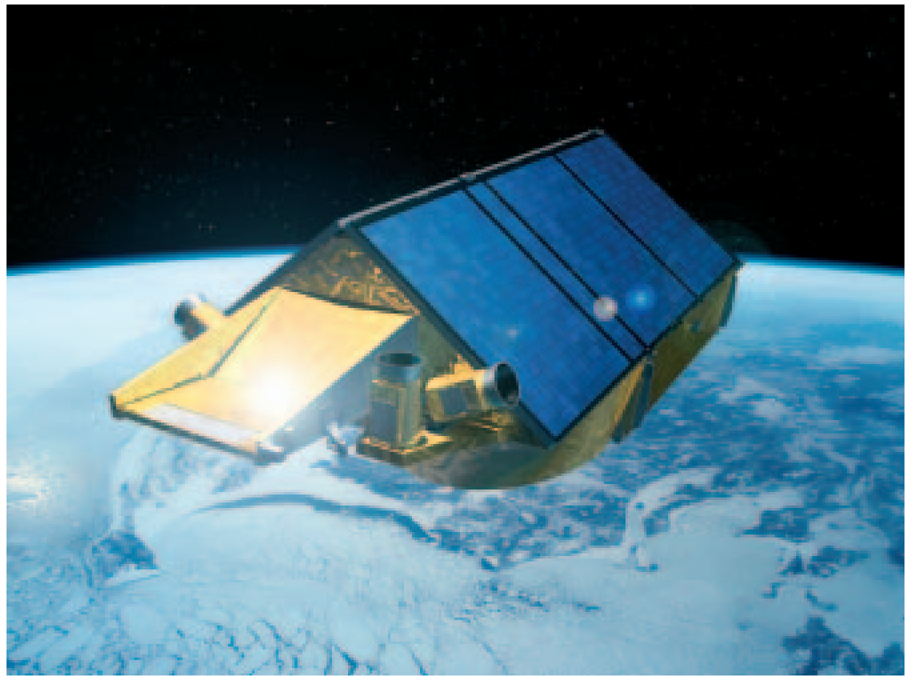
In the preceding article Prof. Duncan Wingham has outlined the genesis of CryoSat, its scientific objectives and its programmatic constraints. The mission objectives are characterised by the determination of small height-related changes over a three-year period. This imposes requirements on the type 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



Artist's impression of CryoSat in orbit, flying almost towards the viewer. The prominent features visible are the solar arrays, giving a roof-like appearance, and the three star trackers which are mounted on the rigid structure supporting the SIRAL antennas. The structure forming the 'nose' at the very front of the satellite is a thermal radiator for the heat generated by the SIRAL instrument

Altimeter, and this indicates where improvements have been made in the instrument concept. As well as a conventional mode, which offers continuity with earlier missions, SIRAL can also operate in so-called 'synthetic-aperture mode'. This increases the along-track resolution, enabling it to more readily distinguish the narrow 'leads' of open water between sea-ice floes. Over the rough terrain at the edges of the major ice sheets, this increased along-track resolution is further augmented by across-track interferometry using the second antenna and receive channel. The derived angle of arrival of the radar echoes allows more precise identification of the point from which the echo came.

SIRAL makes measurements of the range to the surface that are very precise: each has an uncertainty of just a few tens of centimetres. The averaging of many such measurements brings the system performance to the level needed to satisfy the mission objectives. However, the precise measurement of range alone is insufficient. The exact position of the satellite at the time of each measurement is needed to convert this simple measure of range into something scientifically meaningful, which is the height of the surface above some known reference. We may talk loosely of height above sea level, but in this demandingly precise application we refer to height above a 'reference ellipsoid' – an exactly defined, almost spherical surface that closely approximates to the shape of the Earth. To determine the satellite's position, and thus its height above this reference ellipsoid, measurements from some further payload items are needed.

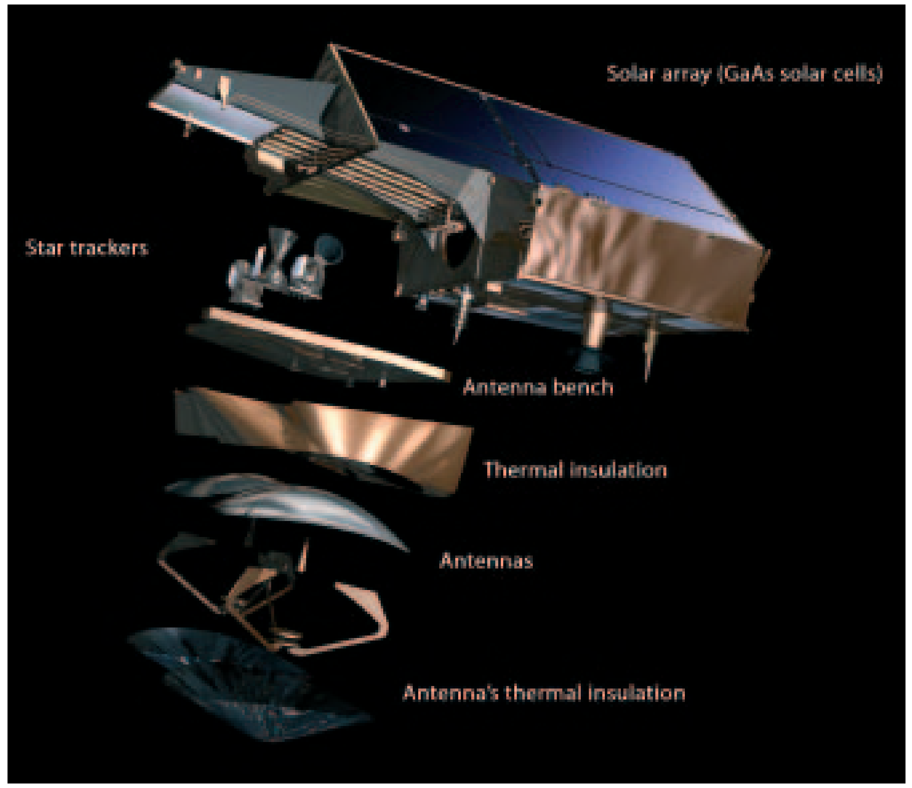
CryoSat includes a DORIS Receiver, a special radio receiver that picks up signals from a network of more than 50 transmitting stations evenly spread around the Earth. By measuring the Doppler shifts of these signals, the range-rate to each one can be determined. The accuracy of the orbit that may be computed from such a dataset obviously depends on several factors, not least the precision and accuracy of the Doppler-shift measurements. In this DORIS excels, and for over a decade the system has been the foremost means of making routine, high-precision orbit determinations. The DORIS receiver is augmented by a passive laser retro-reflector, which allows precise range measurements to be made by ground-based laser-ranging stations.

The final item in this collection of high-precision payload equipment is a set of star trackers, needed to complement the SIRAL interferometer measurement. SIRAL measures the angle of arrival of the echo in its own reference frame, i.e. with respect to the line joining the centres of the two antennas, the 'baseline'. Before that information can be used to identify the exact position on the Earth, we must know the orientation of that baseline, and in order to meet the mission objectives this measure must also be precise to within 30 arcseconds. This is the angle subtended by a football at a distance of 2 km.

The scientific mission objectives not only defined the type and accuracy of the measurements that had to be made (which led to the payload selection), but also their location and timing. As Prof. Wingham explains in the previous article, this 'where and when' is encapsulated in the definition of a specific orbit for CryoSat. The orbital inclination is 92° (and therefore retrograde), with a mean altitude of about 720 km, the exact altitude being defined by the required track-repeat characteristics. This orbit is not one of the class known as 'Sun-synchronous', for which the orbital plane maintains a fixed orientation with respect to the Sun, because, as we shall see later, this would have impacted on the satellite's design.

Designing the System

The full CryoSat system has several parts, and although 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



Exploded view of the CryoSat spacecraft

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 precursor, '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 of CryoSat's design from the mission's requirements and constraints, 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 be 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 antennas point towards the Earth's surface to within a few tenths of a degree, and furthermore that the two antennas are side-by-side as the satellite flies. This means that rotating the satellite to face the Sun is out of the question. Mechanisms on satellites are very costly and so the 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 in the first place, 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 introducing fold-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 knowledge of this assembly is vital to the mission performance, and the design has a number of special features to ensure this. In the calm environment of space, the principal enemy of stability is heat, which causes expansion. The first line of defence against that is to use materials that are least susceptible to it. We have mainly used Carbon-Fibre Reinforced Plastic (CFRP), which has a coefficient of thermal expansion close to zero. It is used for the antennas themselves and also for the substantial 'bench' on which they are mounted, and for the mounts for the star trackers fitted to this bench. We have also used invar, a low-expansion metal originally used for the pendulums of

Parameter	LRM	SAR	SARIn
Receive chain	left	left	left and right
Centre frequency		13.575 GHz	
Bandwidth		350 MHz	
Transmit power		25 W	
Noise figure		1.9 dB at duplexer output	
Antenna gain		42 dB	
Antenna 3 dB beamwidth (along-track)		1.0766°	
Antenna 3 dB beamwidth (across-track)		1.2016°	
Interferometer baseline	–	–	1.172 m
Samples per echo	128	128	512
Sample interval		0.47 m	
Range window	60 m	60 m	240 m
PRF	1970 Hz	17.8 kHz	17.8 KHz
Transmit pulse length		49 µs	
Useful echo length		44.8 µs	
Burst length	–	3.6 ms	3.6 ms
Pulses per burst	–	64	64
Burst repetition interval	–	11.7 ms	46.7 ms
Azimuth looks (46.7 ms)	91	240	60
Tracking pulse bandwidth	350 MHz	350 MHz	40 MHz
Samples per tracking echo	128		
Tracking sample interval	0.47 m	0.47 m	3.75 m
Size of tracking window	60 m	60 m	480 m
Averaged tracking pulses (46.7 ms)	92	32	24
Data rate	51 kbps	11.3 Mbps	2 x 11.3 Mbps
Power consumption	95.5 W	127.5 W	123.5 W
Mass		62 kg	

Key characteristics of the SIRAL

clocks.

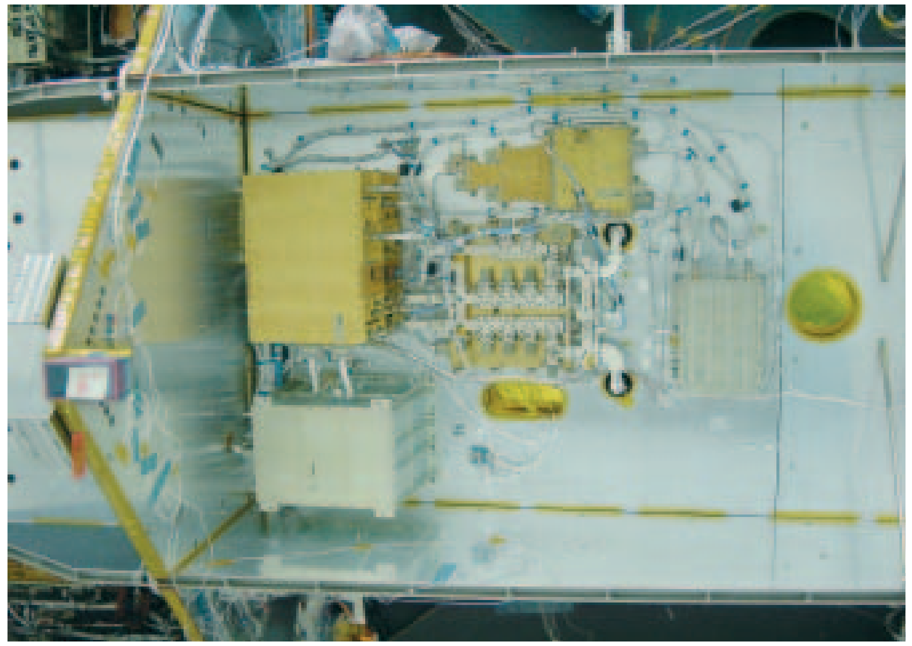
However, the majority of the satellite is made of aluminium, and so another vital part of the defence is isolation. The sensitive antenna bench is attached to the rest of the satellite by a three-point quasi-isostatic suspension, which minimises the transfer of thermal distortions and heat variations. The theme of isolation is carried further by the wrapping the bench and all its attachments with multi-layer insulation; even the antenna apertures are protected from the hot Sun by an exotic single-layer insulation coated with germanium.

The Payload: Re-use and innovation

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.

A less obvious but far more pervasive change was the new need for phase stability, introduced by both the SAR and interferometric functions. Phase had never been an issue with previous altimeters, but for SIRAL it is critical. Consequently, the SIRAL development effort has seen much analysis, measurement, characterisation, optimisation and tuning, as well as the introduction of some special means of calibrating phase performance in flight.



The SIRAL electronic equipment mounted in the nose of the satellite

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 bench. 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-fed design. The entire assembly went through a measurement campaign that challenged the capabilities of the test facility due to the exacting phase-measurement requirements.

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 science 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 over a 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 in 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 user-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 Doppler measurements goes through 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

possibility of encoding information on the uplinked signals, and two privileged master beacons, 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-rotation 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 position, 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 in 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 rather 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 retro-reflector, 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 MetOp mission, with the frequency and bandwidth reused from an allocation originally given to EnviSat.

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 satellite's orientation with respect to the stars, which together with the DORIS time and orbit information allows the onboard software to calculate the satellite's orientation with respect to the 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 ferrite 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 'backstop' 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 the same as the weight of 1 cc 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 two 40 mN thrusters to maintain the orbit in the face of air-drag, eventually consume the 35 kg of pressurised nitrogen onboard.

The attitude-control system has other sensors too, which are used during the initial stabilisation after separation from the launcher, and in emergencies. These are a set of magnetometers and an ingenious 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-

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.

Mission Orbit

Type:	LEO, non-Sun-synchronous
Repeat cycle:	369 days (30 day sub-cycle)
Mean altitude:	717.212 km
Inclination:	92°
Nodal regression:	0.25° per day

Payload
SIRAL (SAR/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 Retroreflector 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.
- SIRAL antennas on isostatically mounted plate with Star Trackers.

Dimensions
4.60 m x 2.34 m x 2.20 m

Mass
670 kg (including 36 kg of fuel).

Power
- 2x GaAs 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.
- Gaseous-nitrogen propellant (36 kg at 250 bar).

Spacecraft Attitude
- Three-axis-stabilised local-normal pointing, yaw-steering, with 6° nose-down attitude.
- Star trackers, magetometers, magetotorquers and 10 mN cold-gas thrusters.
- < 0.1° pointing error; < 0.001°/s stability.

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

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

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

Launch Vehicle
Rockot (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.

CryoSat in the EMC chamber at ESTEC in Noordwijk

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. This is an inescapable ordeal and involves a long programme of 'torture' for the satellite. CryoSat had its mass properties (centre of gravity, moments of inertia, etc.) measured before it was attached to the launcher-separation system and shocked, as the explosive separation bolts fired. It was then clamped to a large table and severely shaken to simulate the effects of launch. Thereafter, it has been put into a sealed chamber and bombarded with all manner of electromagnetic signals to test its resistance to interference from the space environment, the launcher, and even from itself.

Next it will be exposed to vacuum, simulating the extremes of solar 'cooking' and the chill of deep eclipse. The final test will see CryoSat placed in an acoustic chamber in which large horns will generate a sound field so intense that it would instantly deafen any engineer present – this simulates the extreme sound pressures experienced inside a launcher's fairing during flight.

In between times, CryoSat is constantly being probed and measured, both as diagnostics and status checking, and to verify that the Mission Control Centre is able to flawlessly monitor and control it.

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 vehicle, called 'Rockot', is a converted SS-19 inter-continental ballistic missile, with a versatile, re-startable upper stage known as Breeze-KM. The launch will take place from 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.

CryoSat on the shaker at ESTEC for vibration testing