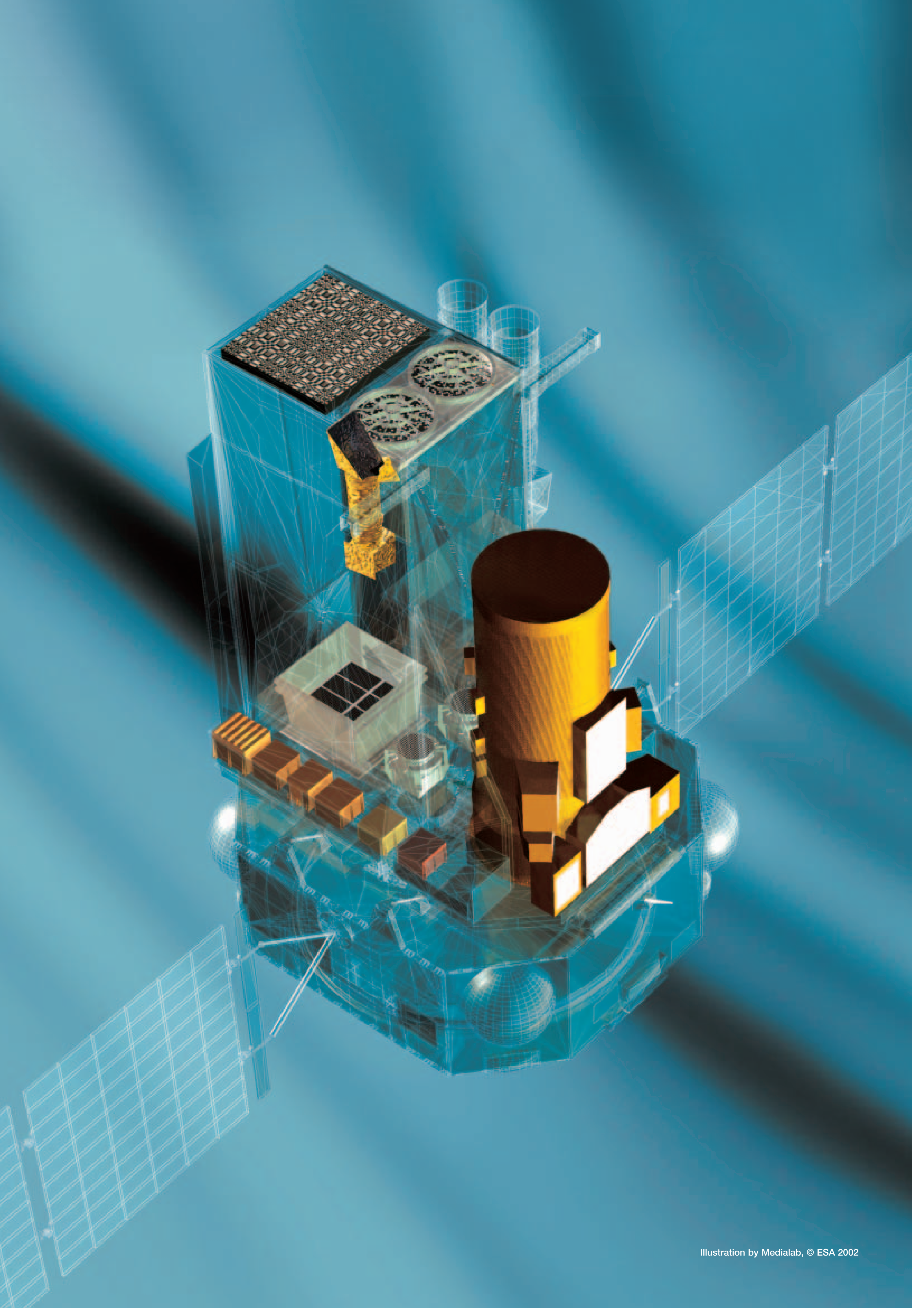


Integral – Ready to Fly!

K. Clausen, P. Sivac, P. Jensen, B. Henson, E. Balaguer, L. Popken, P. Strada, C. Tirabassi & P. Rumler
Integral Project Team, ESA Directorate of Scientific Programmes, ESTEC, ESTEC, Noordwijk, The Netherlands

The International Gamma-Ray Astrophysics Laboratory (Integral) is a truly international enterprise. While ESA is responsible for the overall mission, the satellite's development and the flight operations, the launcher is provided by the Russian Space Agency and the second ground station is provided by NASA. The scientific instruments and the Science Data Centre are provided by the mission's Principal Investigators, with funding from national organisations.

The Integral project was approved in 1993 and the hardware phase was started in 1996. After a long and difficult development phase dominated by the design and manufacture of Integral's complex scientific instruments, the flight model has been successfully tested during the past year and was recently shipped to Baikonur for launch on a Proton rocket.

Introduction

Integral is an astronomy observatory that detects gamma-rays, which lie at the most energetic end of the electromagnetic spectrum. Its aim is to provide an unprecedented, high-resolution imaging capability for the unambiguous identification of gamma-ray sources, and high-energy-resolution line spectroscopy. Due to the low photon flux, which decreases with higher energies, and due to the high penetrating power of gamma-rays, large-area detectors and heavy shielding are required. Unlike visible light and X-rays, gamma-rays cannot be reflected by mirrors. Their imaging is therefore especially cumbersome and has to be based on the coded-mask technique, which again involves high masses and large dimensions. This means that a gamma-ray mission cannot be achieved with a mini-satellite and Integral is therefore a very large and complex spacecraft – in fact it is ESA's heaviest scientific satellite ever. It could be implemented as a low-cost mission only by using a common Service Module design for XMM (another ESA scientific mission) and Integral (Fig. 1), and by relying on extensive international cooperation.

The Proton launch, planned for 17 October 2002 at 4:41:00 (UTC), will put Integral into a highly eccentric 700 km x 153 000 km transfer orbit inclined at 51.6° to the Equator, and with

Figure 1. The Integral flight-model satellite, with solar arrays deployed, in the ESTEC test facilities. Inset, the XMM satellite with which it shares a common Service Module design (lower part)

its apogee in the Northern Hemisphere. Separation of the spacecraft from the launcher's upper stage will take place 1.5 h after lift-off. The Mission Operations Centre (MOC) located at ESOC in Darmstadt (D) will then assume control of the satellite using ground stations at Redu in Belgium and Goldstone in California. After the initial checkout, the first five orbits will be used to commission the spacecraft and to raise the orbit's perigee from 700 to 10 000 km, to escape the destructive effects of the Earth's radiation belts on the performance of the scientific instruments. This will be followed by a five-week performance-validation phase for the scientific payload. Thereafter, Integral will be ready to begin observations for the scientific community, hopefully making many unprecedented discoveries in the field of high-energy astrophysics during its five-year operational lifetime.

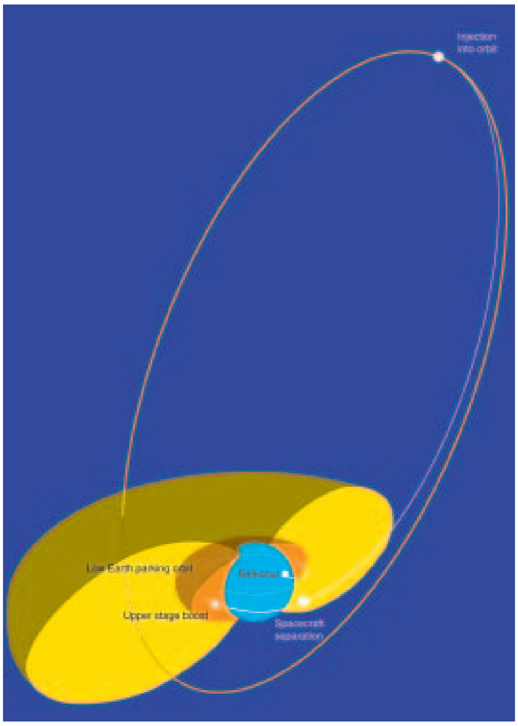


Figure 2a. Schematic of Integral's operating orbit and a cutaway view of the radiation belts in yellow

The Integral payload consists of two large gamma-ray instruments:
- an Imager (IBIS)
- a Spectrometer (SPI)

and two monitoring instruments:
- two identical X-ray monitors (JEM-X)
- an Optical Monitoring Camera (OMC).

These instruments are co-aligned and will observe the same celestial objects over the full wavelength range extending from the visible to high-energy gamma-rays.

The mission

Integral will be launched on a three-stage Proton rocket, with a Block DM upper stage that is capable of several separate ignitions, thereby allowing a variety of different injection orbits from circular to highly eccentric. After many detailed studies, an inclined, highly eccentric orbit with the following characteristics and its apogee in the Northern Hemisphere was finally selected:

Apogee height	153 000 km
Perigee height	10 000 km
Inclination	51.6 deg
Period	3 d
Maximum eclipse	1.8 h

This orbit was preferred over a more circular one due to the simpler injection scenario, which is less demanding on the satellite's thermal and power subsystems. The chosen orbit also means that Integral will spend 84% of its time above an altitude of 60 000 km and hence completely outside the Earth's potentially very damaging radiation belts (Fig. 2a). This will provide perfect conditions for undisturbed,

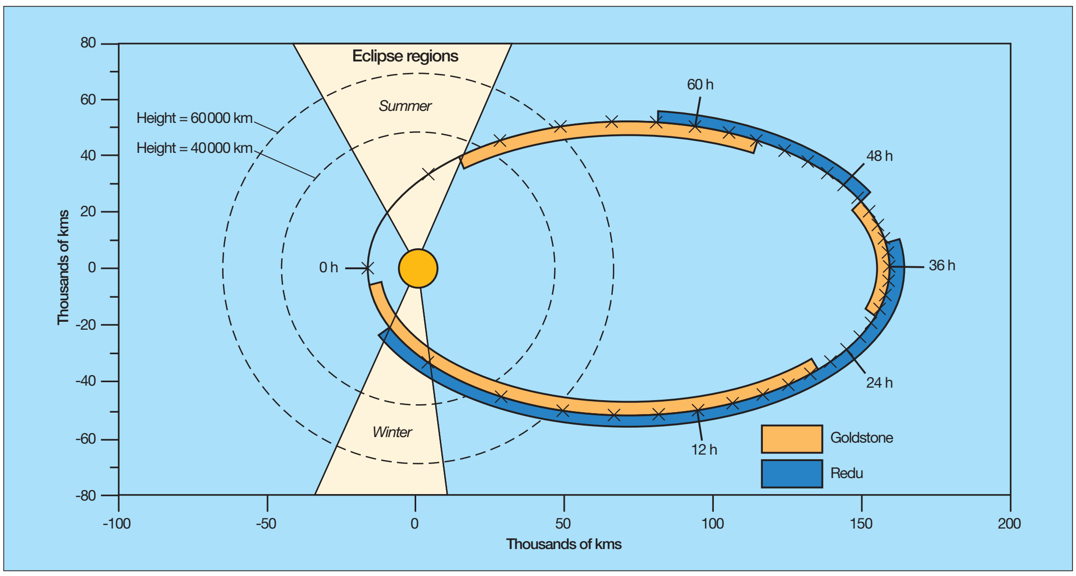


Figure 2b. Eclipse regions and telemetry coverage from the Redu (B) and Goldstone (USA) ground stations immediately after launch

long-duration real-time scientific observations, which is one of the mission's primary design requirements. The two ground stations, Redu (B) and Goldstone (USA), together provide complete telemetry coverage for satellite altitudes above 40 000 km (Fig. 2b).

System design

The spacecraft configuration was driven by: the decision to re-use the XMM Service Module design, the mass and field-of-view requirements of the instruments, and the constraining dimensions of the Proton fairing (Table 1). The basic programme requirement that the Integral satellite should be compatible with either an Ariane-5 or Proton launch posed interesting design challenges. It required all mechanical and electrical interfaces, the environmental requirements, and the spacecraft envelope to be established for design integrity with both launchers.

The large mass of the Spectrometer (SPI) and the minimum focal length of the Imager (IBIS) presented serious centre-of-gravity and fairing envelope problems, besides the need to distribute the heavy loadings into the Service Module structure. Nevertheless, with the help of local cut-outs in the fairing insulation and by rounding off the corners of the upper part of the Payload Module, almost perfect balancing of the satellite has been achieved.

The tight fairing envelope also influenced the accommodation of the telecommunications antennas. By placing them on short booms at diagonally opposite corners of the Service Module, the desire to avoid deployable booms and the envelope constraints were both satisfied. A dedicated radio-frequency mock-up test was performed to verify the provision of full spherical coverage by the antennas.

The spacecraft's Reaction Control System has four tanks filled with 540 kg of hydrazine, most of which will be used for the perigee-raising manoeuvre. The remainder will be available for off-loading the reaction wheels during routine satellite operations. The usual horizontal transportation of the Proton launcher to the launch pad precluded re-use of the XMM internal tank design for Integral. The tank had to be redesigned to incorporate a diaphragm separating the pressurant from the fuel, to avoid the ingestation of gas into the fuel pipes during the horizontal transportation. Also, the orientation of the 20 N thrusters had to be reversed compared with the XMM layout because of the asymmetric nature of Integral's Payload Module (maintaining the XMM layout would have caused a high disturbance torque due to plume impingement).

Table 1. Main spacecraft design drivers and constraints

Area	Main Design Drivers & Constraints
Compatibility with Proton and Ariane-5 Launchers	• Fairing envelope • Horizontal launcher transportation after satellite hydrazine filling • Environmental loads during launch • Radiation environment after injection
Commonality with XMM	Minimise changes to: • System design • Unit design • Onboard resources
Science requirements	• Undisturbed observation; maximise time above 40 000 km • Real-time operation (observatory) • Focal length of the instruments • Co-aligned instruments
Ground-segment outage	36 h of onboard autonomy
Other requirements	Reduce the use of gyros to ground-controlled events

The Attitude and Orbit Control Subsystem (AOCS) maintains the three-axis stabilisation of the satellite, using a star tracker, fine Sun sensors, and reaction control wheels for the fine-pointing mode. The AOCS for Integral has its own attitude-control computer and a set of additional sensors for failure detection. It was modified to fulfil the additional design requirement of using gyros only when they can be checked out in advance of their application, following the 'lessons learned' from in-orbit gyro failures in the past. This implied the development of a solid-state gyro package, which is based on the principle of a vibrating fork and its sensitivity to satellite rotation. The gyro package is to be used for the emergency recovery mode if satellite attitude control should be lost. The package is always active and, in principle, has an unlimited lifetime.

Dedicated star-tracker baffles were developed to achieve the required attenuation of stray light caused by the larger Sun angle. In addition, because of the mission characteristics and the spacecraft's mass properties, modification of the AOCS control algorithms and corresponding software was also required.

Integral's power subsystem is based on a 28 V regulated power bus. It comprises the main regulator unit, the solar arrays (SA), two NiCd batteries, two power-distribution units (one PDU for each Module), and a pyrotechnic control unit to release the solar arrays and initiate activation of the satellite after its separation from the launcher. The two deployable solar-array wings, each with three

Table 2. Integral facts and figures

Mission	**International Gamma-Ray Astrophysics Laboratory**	
Objective	Fine imaging and spectroscopy of celestial gamma-ray sources in the energy range 15 keV to 10 MeV	
Instruments:	Energy:	Instrumentation:
Imager	15 keV–10 MeV	Coded-aperture mask 16 384 CdTe detectors (each 4 x 4 mm^2) 4096 CsI detectors (each 8.4 x 8.4 mm^2)
Spectrometer	20 keV–8 MeV	Coded-aperture mask 19 Ge detectors (each 60 mm diam.) actively cooled to 90 K
X-ray Monitor	3–35 keV	Coded-aperture mask Micro-strip detector (diam. 250 mm) Xe/CH_4 gas
Optical Monitor	500–600 nm	CCD detector, refractive optics
Launch Vehicle	Proton with Block DM upper stage. Launch from Baikonur.	
Operational orbit	Perigee height Apogee height Inclination Argument of Perigee RAAN Period Max eclipse	10 000 km 153 000 km 51.6 deg 300 deg 105 deg 3 days 1.8 hours
Ground stations	Redu (Belgium) and Goldstone (California) Coverage 100% above 40 000 km	
Lifetime	2.2 years nominal – 5.2 years extended	
Dimensions	Satellite body: 2.8 m x 3.2 m x 5 m Solar-array span: 16 m	
Mass	Total mass Dry mass Fuel (hydrazine) Instrument mass	3954 kg 3414 kg 540 kg 2013 kg
Power/energy Storage	28 V regulated power bus Advanced rigid solar arrays, silicon cells Launch/2.2 years Two 24 Ah NiCd rechargeable batteries	 2377/1960 W, SAA 0 deg 1834/1630 W, SAA 40 deg
Solar Aspect Angles (SAA)	40° nominal mission, 30° extended mission	
Communication	S-band up- and down-links, 2 fixed antennas Telemetry rate Telecommand rate	 91 kbps 2 kbps
Mechanical Properties	First axial mode First lateral mode Load case 1 Load case 2	> 38 Hz > 12 Hz ± 9 g longitudinal, ± 1.5 g lateral ± 0 g longitudinal, ± 4.5 g lateral
Pointing and alignment	Three-axis-stabilised spacecraft Absolute pointing error Instrument alignment knowledge	 5 arcmin (Y,Z) 15 arcmin (X) 1 arcmin (Y,Z) 3 arcmin (X)

rigid panels, provide 2 kW of power during sunlit periods at beginning-of-life. The two rechargeable NiCd batteries (each with 24 Ah capacity) power the satellite during eclipse. Originally, these batteries were specifically selected for Integral due to its longer eclipse durations, but the same type were also eventually chosen for XMM due to an orbit change for that mission. The Payload Module PDU and all of the wiring harnesses are Integral-specific designs.

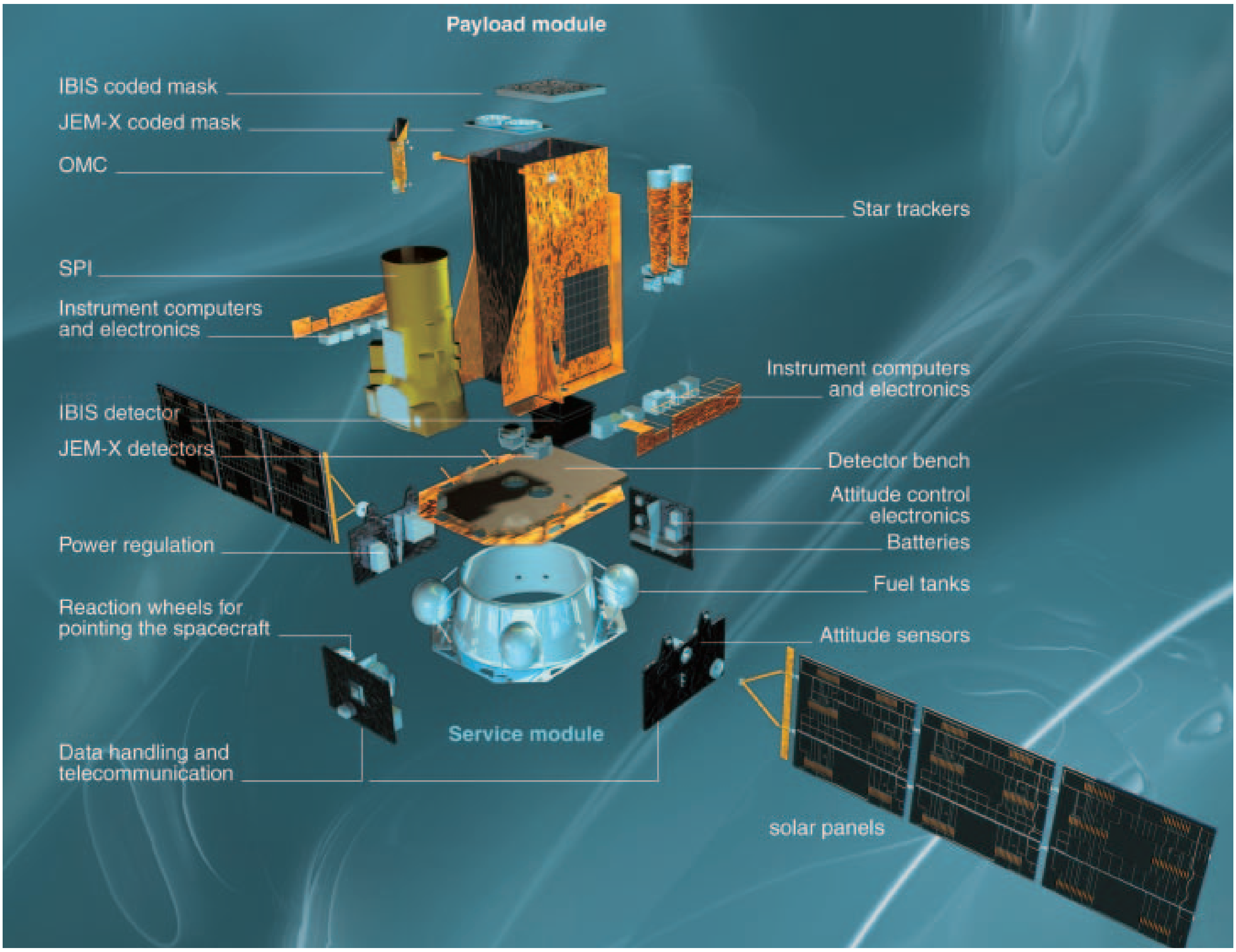
The Onboard Data Handling (OBDH) subsystem's main functions are to distribute commands, to sample/format telemetry data, and to provide data-processing services. The OBDH is built around the ESA standard OBDH bus and is fully compatible with the ESA Standards for Packet Telemetry and Packet Telecommands. The system consists of a Command and Data Management Unit (CDMU) and two Remote Terminal Units (RTUs), one for each Module. Both real-time and time-tagged commanding capabilities are supported. Processing services are provided for spacecraft control, monitoring of its health and resources, maintenance and distribution of spacecraft time, as well as the storage of minimum monitoring data during periods of satellite non-visibility. The OBDH's design is basically identical to that of XMM, with a few important exceptions: the telemetry rate has been increased to 91 kbps to satisfy the data-rate requirements from the scientific instruments, which has implied adjustments also to the telemetry carrier modulation.

Several new software modules have been developed and implemented to satisfy the requirement for 36 hours of satellite autonomy in the event of a ground-station outage. This includes, in particular, on-board monitoring of any sampled housekeeping parameters and overall thermal-status monitoring in order to identify and isolate any system anomalies and initiate autonomous recovery if any such malfunction should occur.

A summary of the main Integral facts and figures is given in Table 2.

Figure 3 is an exploded view of the complete Integral satellite.

Figure 3. Exploded view of Integral showing the Service Module (lower part) and Payload Module (upper part)



Assembly, Integration and Verification (AIV)

The satellite system AIV flow was based on three models (Table 3):
- a Structural Thermal Model (STM), to qualify the satellite's structural and thermal design and to validate the relevant mathematical models
- an Engineering Model (EM), to verify system functionalities and performance and to qualify the design in terms of Electromagnetic Compatibility (EMC) and Electrostatic Discharge (ESD)
- a Proto-Flight Model (PFM), which is actually the flight unit.

Table 3. Satellite system tests

System Test	STM	EM	PFM
Modal survey	X		
Sine vibration	X		X
Clamp-band release	X		X
Acoustic	X		X
Solar-array deployment			X
Thermal balance/thermal vacuum	X		X
Alignment checks	X		X
Functional tests		X	X
Payload calibration			X
System validation tests with ESOC			X
Conducted EMC		X	X
Radiated EMC		X	X
ESD		X	
RCS leak and performance checks			X

Each of these system models contributed a large part of the subsystem verification, especially for some elements of the payload that could not otherwise be tested. The alignment of masks and detectors, payload calibration, and detector thermal control are examples of items that could only be tested at system level, due to the particular configuration of the satellite and the instruments.

In the early part of the project, the commonality of the Integral and XMM Service Modules was exploited to optimise the integration and test activities. The largely common Ground Support Equipment (GSE) helped to reduce costs and minimise development risk.

Active co-operation between the XMM and Integal AIV teams was encouraged from the start of the project. Several Alenia AIV engineers participated in XMM-Newton's integration, providing support and ensuring the transfer of experience to the Integral programme. The SVM, STM and EM spacecraft, test rigs and electrical equipment were also reused. The actual test procedures differed somewhat due to the different approaches and integration philosophies of the two prime contractors.

The integration and testing of the complex Integral payload presented the greatest challenge. To avoid problems with instrument integration, ESA provided standardised spacecraft interface simulators for instrument-level testing. Alenia AIV engineers were detached to support the instrument integration activities and to acquire instrument experience for the satellite AIV.

Delays in the delivery of the Integral flight-model instruments resulted in a rethinking of the spacecraft flight-model test campaign in order to save as much time as possible between the last instrument delivery and launch. Whereas the STM campaign had been divided between ESTEC in Noordwijk and IABG in Munich, the FM campaign was conducted completely at ESTEC, which simplified the logistics and thereby saved time (Figs. 4 & 5). The alignment philosophy was also modified: instead of using a rotary table, which limits the number of activities that can be conducted in parallel with the alignment work, the satellite was kept fixed on the integration stand and the measurements were made with a number of 'roaming' theodolites, communicating wirelessly with a base computer. This allowed integration and test activities to continue in parallel, allowing considerable compression of the AIV schedule.

Movement of the satellite between tests was also kept to a minimum, because the Spectrometer required two vacuum pumping systems to be connected and a helium cooling circuit for ground operation. The EMC system test was therefore performed in the ESTEC integration area, with the satellite surrounded by moveable anechoic walls. The instrument calibration campaign was performed with radioactive sources suspended from the crane bridge in the ESTEC clean room, moving the bridge back and forth to illuminate the satellite under various incidence angles. The exact positions of the sources with respect to the satellite were then reconstructed using theodolites.

A number of tests could not be compressed or optimised further, but were nevertheless run as effectively as possible thanks to the dedication of the Industry and ESA teams. Most of the functional testing was performed using shift working. The calibration campaign was run 24 hours per day for two weeks, with the participation of the scientists responsible for all of the high-energy instruments. The thermal-balance test was also conducted within the allocated time span, with two hot exposures and two cold exposures being performed in 19 days.

Launch-campaign preparation

The typical launch campaign for commercial satellites in Baikonur involves a short 'ship and shoot' approach, with very limited access time for satellite preparation. Traditionally, ESA's sophisticated scientific satellites require a longer period for pre-launch preparation and so, to reach a working compromise with our Russian partners, ESA introduced a number of innovations to simplify and speed up the launch-preparation process for Integral.

Firstly, the transport containers were modified to accommodate the two completed satellite Modules. This allowed the solar arrays, Sun sensors, antennas and baffles to be fully assembled prior to shipment to Baikonur. Secondly, the satellite verification needed at the launch site was optimised to include only a post-transport damage check and a reduced instrument and subsystem functional test. A telemetry link is provided to transfer the satellite data from Baikonur

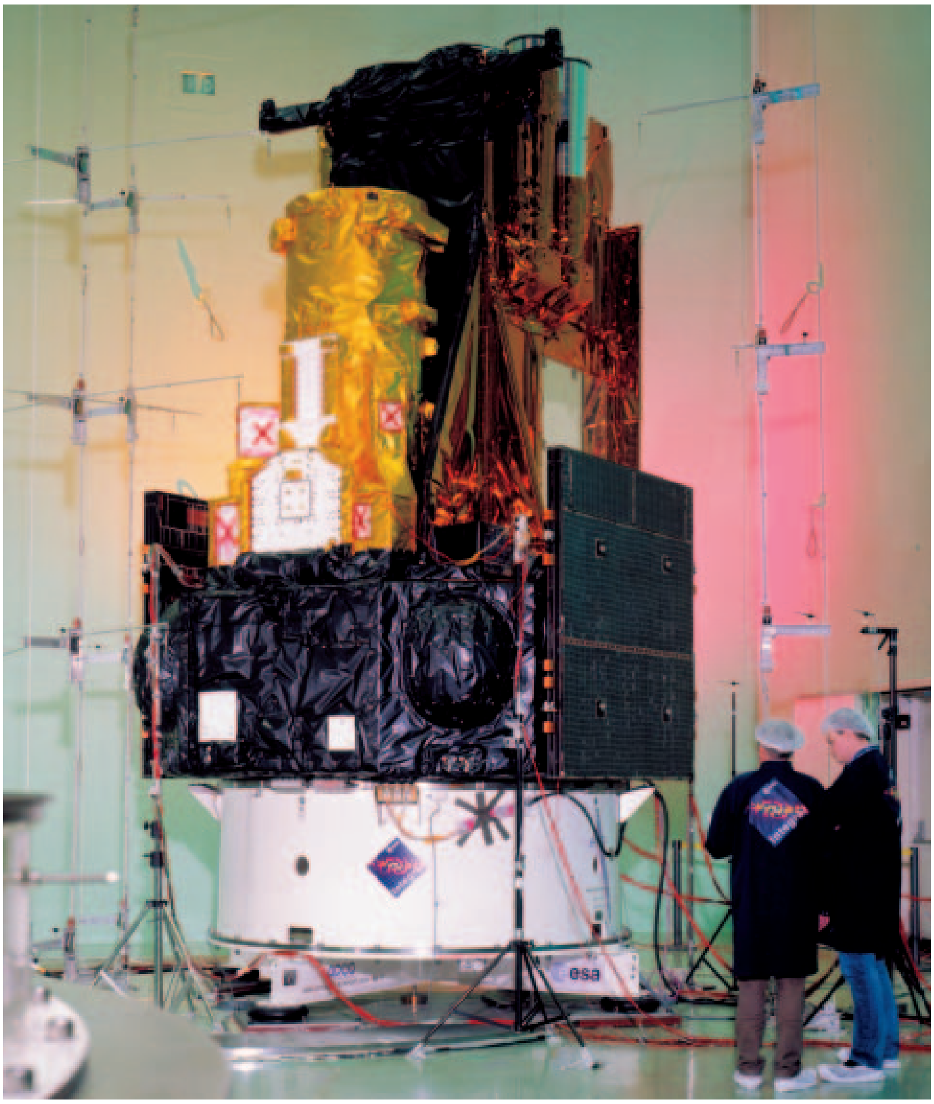


Figure 4. Integral in the Acoustic Test Facility at ESTEC

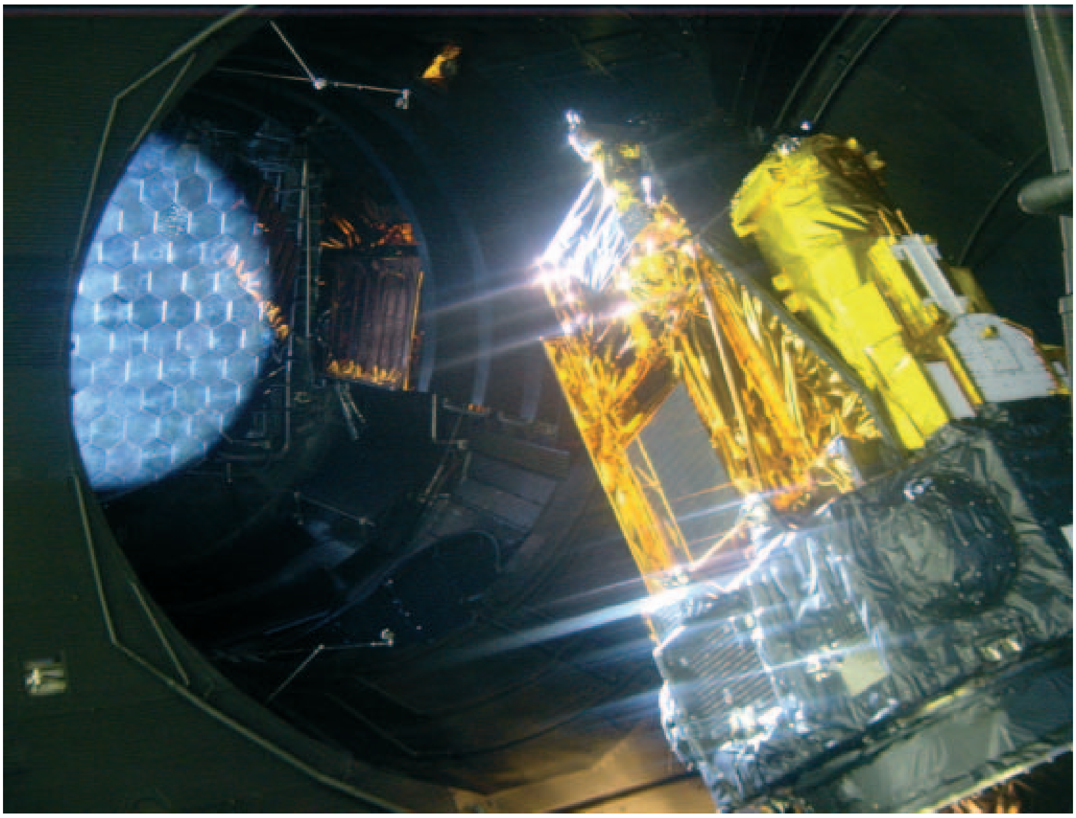


Figure 5. Integral in ESTEC's Large Space Simulator (LSS) for thermal-vacuum testing

to ESOC in Darmstadt, from where the instrument teams will perform their final payload checkouts prior to launch.

The launch campaign starts with the transport of the ground-support equipment to Baikonur in mid-August 2002, followed a few days later by the Service and Payload Modules in an Antonov-124 aircraft.

Project management

Integral's baseline costing was founded on three assumptions:
– provision of the payload through international cooperation
– re-use of the XMM Service Module design
– provision of the Proton launcher by the Russian Space Agency in exchange for scientific data.

All three assumptions were initially a potential threat in terms of continuation with the mission, but all were eventually satisfied, allowing the project development activities to proceed to completion. The Integral project schedule is shown in Figure 6.

Although the international cooperative approach eventually succeeded, the initial stages were sometimes very critical, with key partners pulling out just at the time of payload selection. With no clearly defined instrument consortium, a reshuffling of the cooperative arrangements between Principal Investigators and funding agents had to be performed in early 1995 to save the mission. The payload complement was also critically reviewed and new teams were formed, with ESA taking on a greater role than had initially been foreseen. The interfaces to the satellite data handling were changed, the Industry parts-procurement scheme was made available to the instrument teams, and key technology developments, such as the cryo-coolers, were handled directly by the ESA project team.

Meanwhile, the development of XMM was proceeding at a rapid pace. The idea of re-using its Service Module therefore had to be implemented as quickly as possible in order to benefit from the potential commonality savings. Many options had been considered, ranging from having one prime contractor build both Service Modules in series, to having different two prime contractors sharing a common design. This last option was finally adopted, and a summary of the scheme is shown in Figure 7.

The XMM prime contractor started its procurement activities in 1994, requesting proposals from subcontractors for two flight units, one for XMM and the other to be delivered to the Integral prime contractor. Alenia Spazio was awarded the prime contractorship for Integral soon afterwards, and took over the management of those second units from the XMM subcontractors. This was achieved in a smooth and timely fashion, allowing the subcontractors to organise their manufacturing activities in the most efficient way. Had the two projects drifted apart by more than a year during this period, it is unlikely that the cost savings would have been so great. Close coordination between the ESA project teams was essential to ensure that initial long lead items were financially covered, first via XMM for both units, then by Integral itself under its own contracts.

Change and configuration control in this environment was an initial concern. How would one cope with a design change originating from XMM on Integral? Would the change have to be automatically accepted by the Integral prime

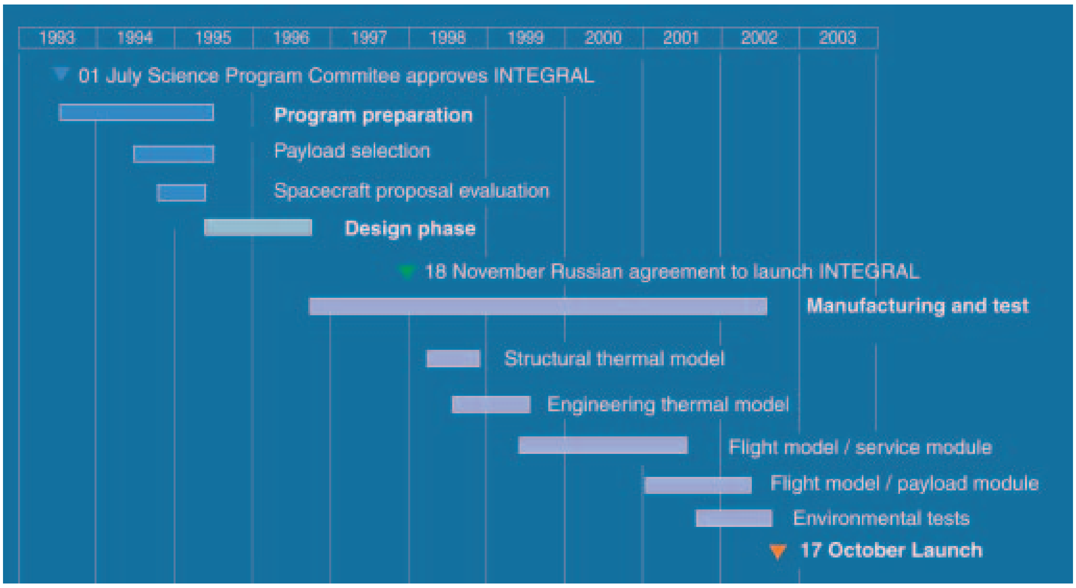


Figure 6. Integral project schedule

contractor? How would one deal with an important non-conformance, or a request for a waiver? A pragmatic, case-by-case approach was agreed to by all parties and proved to be extremely successful, requiring only limited extra coordination between the ESA project teams.

The commonality approach was highly beneficial for the satellite industrial development and was a key factor in allowing the mission to proceed. Some benefits were also obtained in the operations area, although commonality was not implemented as systematically there as on the satellite-development side.

The provision of the launch by the Russian Space Agency in exchange for scientific data has provided a significant cost saving for the Science Programme. It is the first time that an ESA satellite will be launched on a Proton rocket. The Integral Project was directly involved in the adaptation to the fairing and the upper stage, the development of a new adaptor between the satellite and the rocket, and the upgrading of the launch facility to meet Integral's requirements. The co-operation with the Russian contractors in these efforts was very constructive.

Conclusion

Integral has broken new ground in the attempt to increase programme efficiency. Most important has been the approach of having a common Service Module for both Integral and XMM. It required an intensive system design effort by ESA's Integral team and in industry to allow re-use of the XMM Service Module with relatively few modifications, without compromising the Integral mission objectives. This commonality approach has ultimately proved highly successful in terms of savings in development costs, with the sharing of flight spares and the re-use of thermal and electrical models, as well as ground-support equipment. The in-orbit operations feedback from XMM since its launch has also proved valuable for the final Integral design.

Another important Programme decision was to cooperate with the Russian Space Agency concerning the Integral launcher. At the time of that decision, ESA had never used a Russian launcher and the Proton launcher system had not yet entered the Western market. In this cooperation, each side started from a very different engineering tradition, but converged in a long and fruitful process on the definition and adaptation of launcher interfaces and the optimisation of the orbit and orbit injection. The launch campaign has also been thoroughly prepared. The mutual widening of scope in terms of engineering experience and human endeavour has been most rewarding.

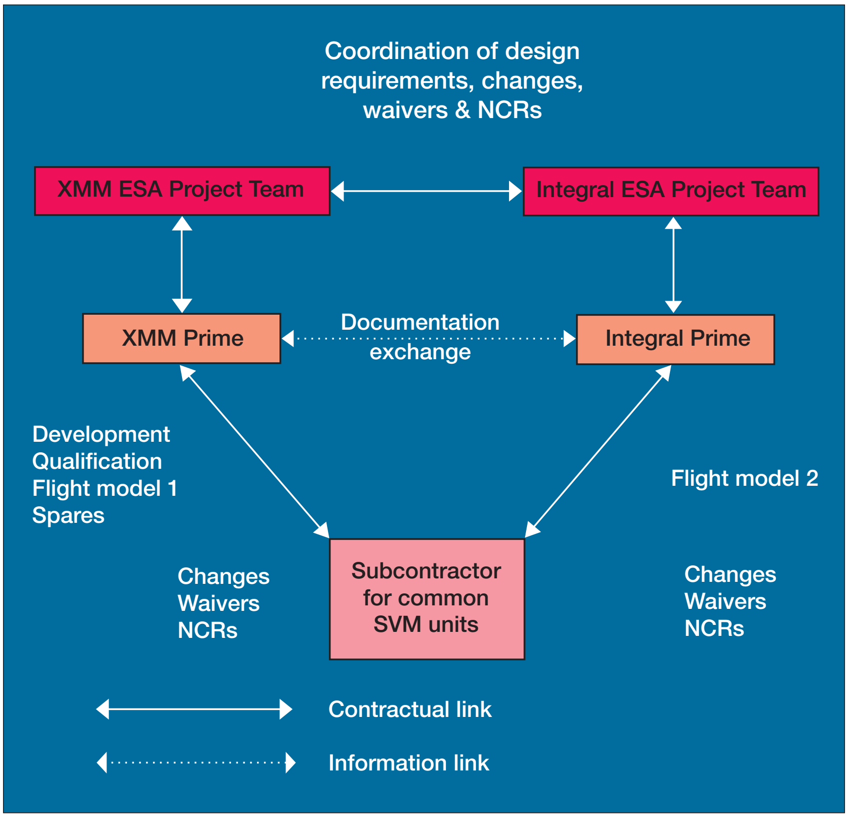


Figure 7. Implementation of the Integral/XMM commonality approach

Integral has now been fully verified on the ground. It has withstood all of the environmental tests conducted at ESTEC during a thorough campaign, in which it was exposed to the vibrations and acoustic inputs of the launch and to the vacuum and thermal conditions of deep space. All of its functions have been re-checked after each test and the satellite has performed exactly as expected.

Integral is ready to fly!

Acknowledgement

The ESA Integral Project Team wish to acknowledge the great efforts and dedication of all of the Principal Investigators teams, the industrial teams spread throughout Europe, and the ESA teams and individuals both at ESTEC and ESOC, who have contributed to making the Integral satellite an outstanding observatory ready for launch. We are especially grateful to the prime-contractor team at Alenia Spazio, Turin, for their dedication, professionalism and excellent spirit of cooperation.