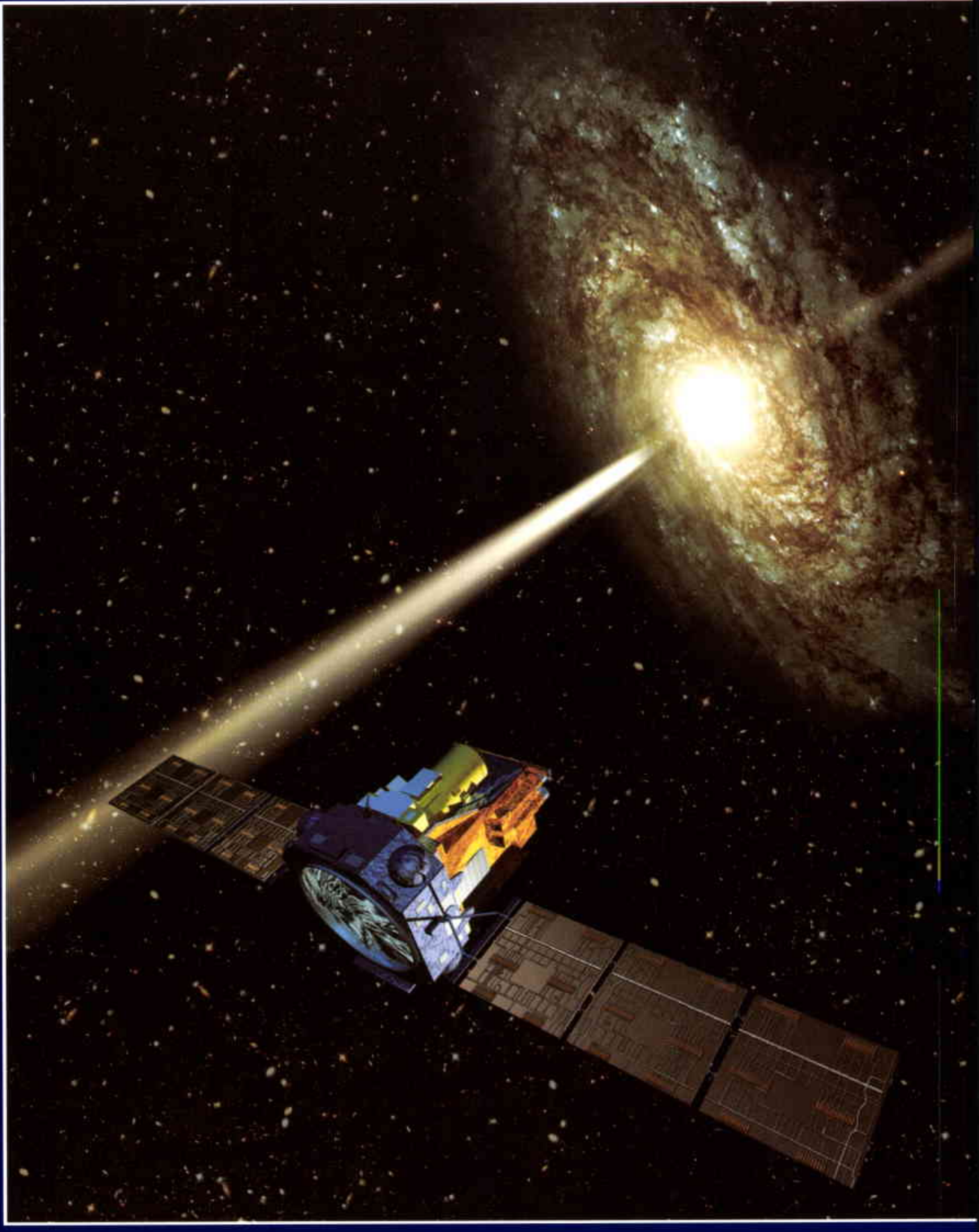
esa bulletin

number 111 - august 2002



European Space Agency
Agence spatiale européenne

european space agency

The European Space Agency was formed out of and took over the rights and obligations of, the two earlier European Space Organisations; the European Space Research Organisation (ESRO) and the European Organisation for the Development and Construction of Space Vehicle Launchers (ELDO). The Member States are Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Norway, Potugal, Spain, Sweden, Switzerland and the United Kingdom. Canada is a Cooperating State.

In the words of the Convention: The purpose of the Agency shall be to provide for and to promote for exclusively peaceful purposes, co-operation among European States in space research and technology and their space applications, with a view to their being used for scientific purposes and for operational space applications systems.

(a) by elaborating and implementing a long-term European space policy, by recommending space objectives to the Member States, and by concerting the policies of the Member States with respect to other national and international organisations and institutions:
(b) by elaborating and implementing activities and programmes in the space field;
(c) by co-ordinating the European space programme and national programmes, and by integrating the latter progressively and as completely as possible into the European space programme, in particular as regards the development of applications satellites;
(d) by elaborating and implementing the industrial policy appropriate to its programme and by recommending a coherent industrial policy to the Member States.

The Agency is directed by a Council composed of representatives of Member States. The Director General is the chief executive of the Agency and its legal representative.

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ESRIN, Frascati, Italy.

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agence spatiale européenne

L'Agence Spatiale Européenne est issue des deux Organisations spatiales européennes qui l'ont précédée – l'Organisation européenne de recherches spatiales (CERS) et l'Organisation européenne pour la mise au point et la construction de lanceurs d'engins spatiaux (CECLES) – dont elle a repris les droits et obligations. Les Etats membres en sont: l'Allemagne, l'Autriche, la Belgique, le Danemark, l'Espagne, la Finlande, la France, l'Irlande, l'Italie, la Norvège, les Pays-Bas, le Portugal, le Royaumi-Uni, la Suède et la Suisse. Le Canada bénéficie d'un statut d'Etat coopérant.

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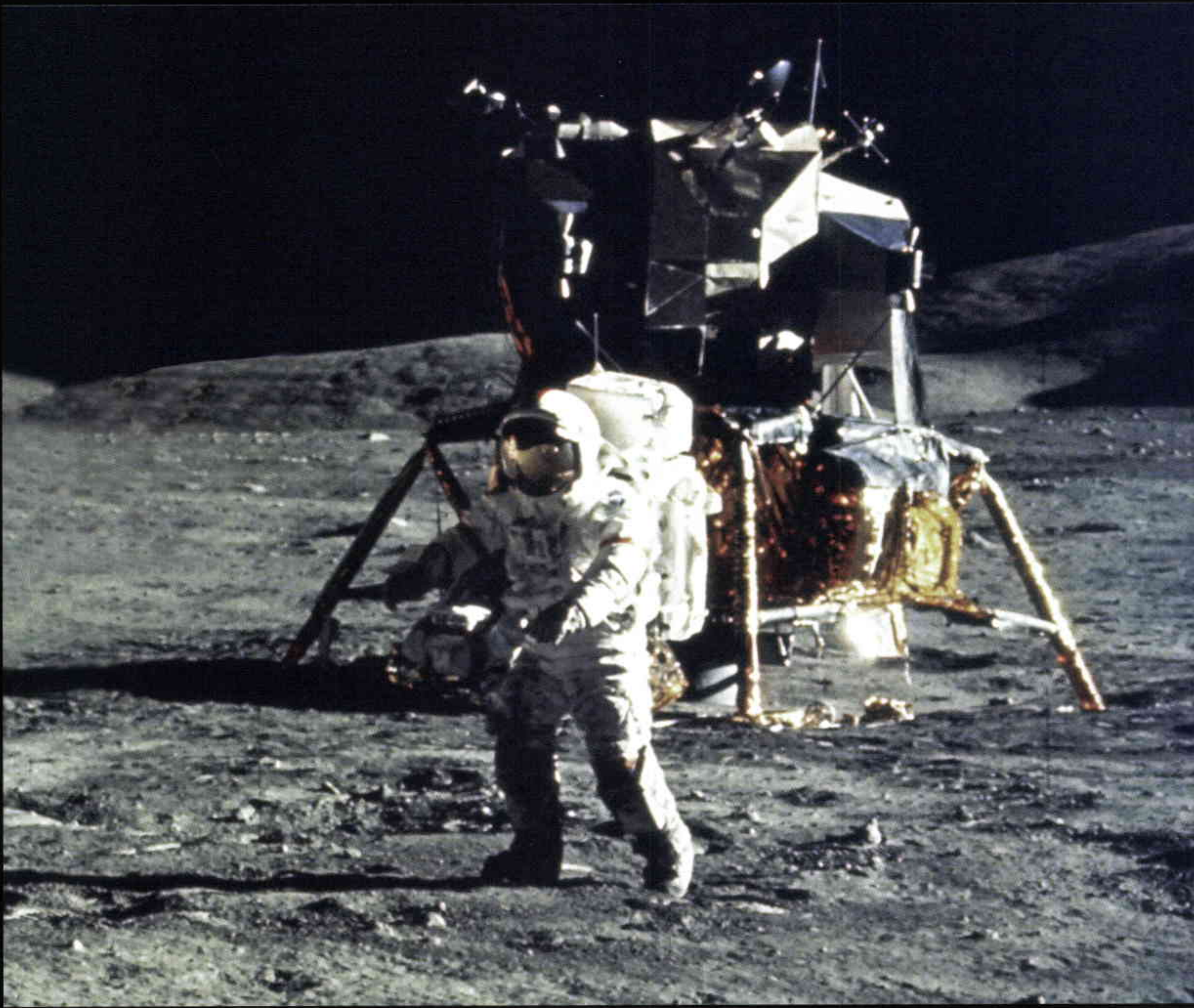

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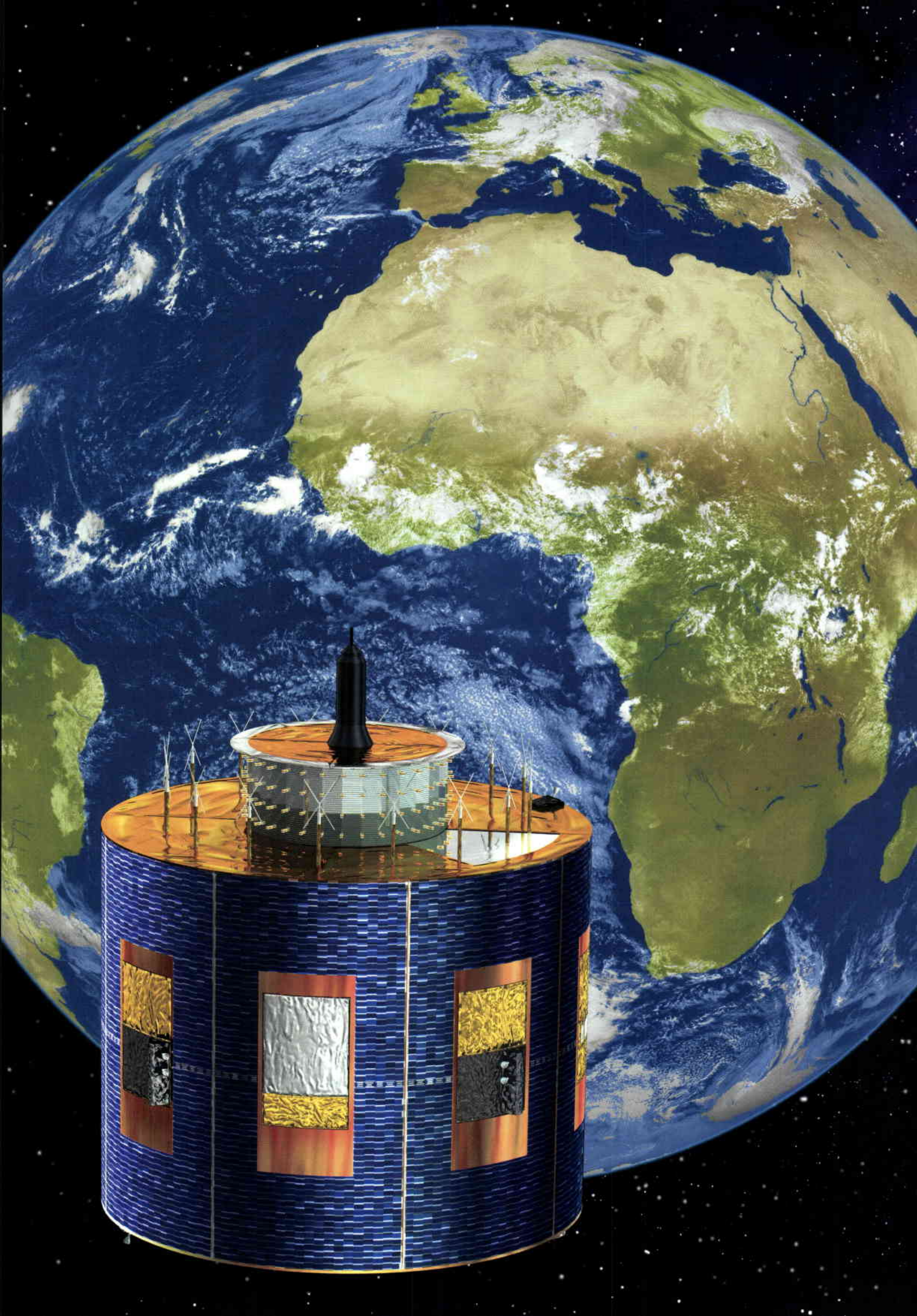

Meteosat Second Generation (MSG)

– A successful ESA-Eumetsat partnership

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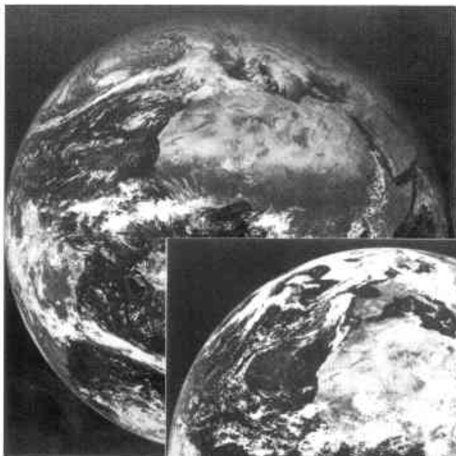
ESA will shortly celebrate the 25th Anniversary of the launch of the first European Meteosat meteorological satellite. The weather-pattern images provided by the Meteosat series of satellites from their geostationary position above the Greenwich Meridian, together with added-value products, such as wind vectors, derived from the raw images, gradually became familiar to professional meteorologists, who started to exploit them in their daily work. When these same images also began to be included in weather reports and forecasts on television and in the newspapers, Meteosat began to be as well known as the presenters.

Once Meteosat had been recognised as an indispensable tool by the European meteorological offices and services, it was clear that ESA had done its job as the satellite initiator and developer and that the meteorological community would prefer to operate the Meteosats themselves. That is how Eumetsat, the European Organisation for the Exploitation of Meteorological Satellites, came to be created back in 1986. Initially, it was a small Secretariat managing the funding from the countries contributing to commonly operate the Meteosats, gradually growing into an organisation employing over 150 staff at its Headquarters in Darmstadt (Germany). The launches of Meteosat-4 and 5 saw the foundation of a successful long-term partnership between ESA and Eumetsat, leading on to the complete handover of the Meteosat system operations to Eumetsat in December 1995, when the seventh satellite in the Meteosat series was launched.

The implementation and optimisation of a remote-sensing mission is a long process. As long ago as the early 1980s, it was evident that Meteosat could and should eventually be improved. Scientists and engineers initiated a series of workshops and meetings to define what would become the next generation of geostationary metorological satellites. Gradually, a concept to continue the Meteosat mission and enhance it was delineated at ESA in consultation with the Eumetsat 'pioneers'. This would ultimately result in the Meteosat Second Generation (MSG) satellite series.

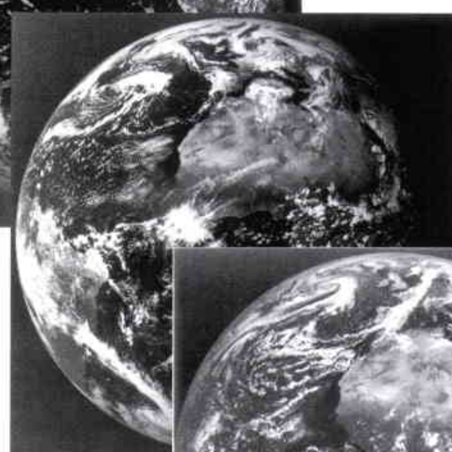
As MSG evolved from a concept into a real project, it was time to discuss with Eumetsat the ways and means of co-operating in meeting such a challenge. The environment had changed from the early 1970s, when ESA alone committed to build Meteosat; now there was Eumetsat, a partner who represented the users' wishes and would fund an important part of the venture. It was therefore agreed that ESA, with its experience in space-system project management and innovation, would run the preparatory studies, which lasted until the early 1990s. Once the design for the system that would meet the needs of the meteorological and climate-monitoring operational communities was ready, the time was ripe to start the corresponding programmes at both Organisations.

That milestone was reached on 17 February 1994, when ESA and Eumetsat signed a Co-operation Agreement encompassing the MSG system and the MSG-1 satellite, followed by the signature of a further agreement relating to MSG-2 and MSG-3 on 16 October 1996. Under these Agreements, ESA undertook to develop and fund the prototype satellite that would become the first in the series of MSG satellites. Eumetsat committed to contribute one third of the cost of the development model and 100% of the cost of the MSG-2 and MSG-3 satellites, which ESA would procure on Eumetsat's behalf. Eumetsat, in turn, would implement the MSG system, comprising a ground segment, three satellites, their launches and in-orbit commissioning and operation of

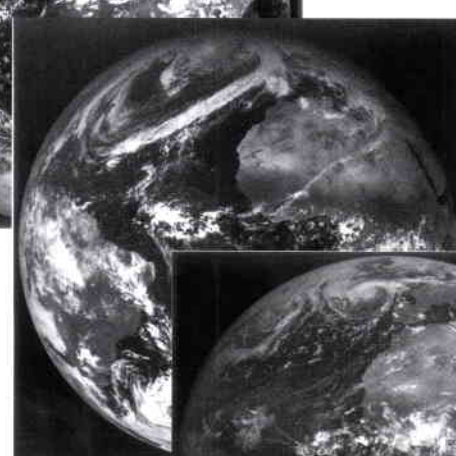

METEOSAT-1


METEOSAT-2


METEOSAT-3


METEOSAT-4


METEOSAT-5


METEOSAT-6

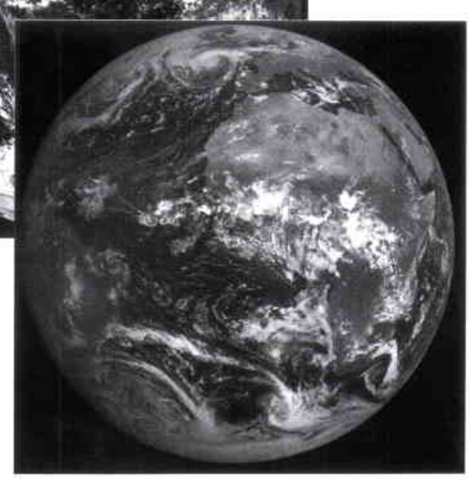

METEOSAT-7

Figure 1. The Meteosat series of seven geostationary meteorological satellites

the system for a period of 12 years. The contract to develop the three MSG satellites was subsequently awarded to a European Consortium led by Alcatel Space Industries (Cannes, F).

The MSG satellites will not only continue and improve the Meteosat mission's role in operational meteorology and climate monitoring, but will also contribute to fundamental research in many Earth-science domains. For this reason, ESA and Eumetsat jointly organised a Research Announcement of Opportunity in 1998, open to scientists worldwide, who proposed innovative projects to use the data from MSG and ESA's Earth-observation satellites. A total of 43 proposals were accepted involving almost 250 scientists.

Now that the first MSG flight model has been successfully launched on an Ariane-5 vehicle from Kourou, it is time to celebrate the success achieved by combining the complementary expertises of the two organisations and to look forward to further successful partnerships in the future.

Figure 2. The ESA and Eumetsat stand at the American Meteorological Society Conference at UNESCO in Paris in June 1998

The MSG System

W. Schumann, H. Stark, K. McMullan, D. Aminou & H-J. Luhmann
MSG Project, ESA Directorate of Earth Observation, ESTEC, Noordwijk, The Netherlands

The MSG System consists of a Space Segment and a Ground Segment. It is designed to provide data, products and services over a system lifetime of at least 12 years, based on a series of three satellites called MSG-1, -2 and -3. The MSG System will perform regular operations with one satellite at the nominal location of 0 deg longitude over the equator, and foresees a stand-by satellite that would be used in case of emergencies or during major configuration changes.

The MSG Space Segment is being implemented by ESA, which is responsible for:
- **the development and procurement of the first satellite, called MSG-1**
- **the procurement, on behalf of Eumetsat, of the two subsequent satellites, MSG-2 and MSG-3.**

The MSG Ground Segment has been developed by Eumetsat and consists of:
- **a control, acquisition, pre-processing and dissemination ground segment composed of central facilities located at Eumetsat's Headquarters, and remote ground stations**
- **an Application Ground Segment, which extracts meteorological and geophysical products from the calibrated and geo-located image data generated by the Mission Control Centre, and performs data-management functions.**

Eumetsat is procuring the launch services for the MSG satellites, on the Ariane launch vehicle, and the Launch and Early Orbit Phase (LEOP) services, which are controlled and provided by ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany.

The mission objectives

As the successor to the first-generation Meteosat Programme, MSG (Fig. 1) is designed to support nowcasting, very-short-range and short-range forecasting, numerical weather forecasting and climate applications over Europe and Africa, with the following mission objectives:
- the multi-spectral imaging of the cloud systems, the Earth's surface and radiance emitted by the Earth's atmosphere, with improved radiometric, spectral, spatial and temporal resolution compared to the first-generation Meteosats
- the extraction of meteorological and geophysical fields from the satellite image data for the support of general meteorological, climatological and environmental activities
- the collection of data from Data-Collection Platforms (DCPs)
- the dissemination of the satellite image data and meteorological information after processing to the meteorological user community in a timely manner for the support of nowcasting and very-short-range forecasting
- the support to secondary payloads of a scientific or pre-operational nature which are not directly relevant to the MSG programme (i.e. GERB and GEOSAR)
- the support to the primary mission (e.g. archiving of data generated by the MSG System).

The mission objectives were subsequently refined by Eumetsat, taking into account further evolutions in the needs of operational meteorology. This updating resulted in:

- the provision of basic multi-spectral imagery, in order to monitor cloud-system and surface-pattern developments in support of nowcasting and short-term forecasting over Europe and Africa
- the derivation of atmospheric motion vectors in support of numerical weather prediction on a global scale, and on a regional scale over Europe
- the provision of high-resolution imagery to monitor significant weather evolution on a local scale (e.g. convection, fog, snow cover)
- the provision of air-mass analysis in order to monitor atmospheric instability processes in the lower troposphere by deriving vertical temperature and humidity gradients
- the measurement of land- and sea-surface temperatures and their diurnal variations for use in numerical models and in nowcasting.

The Imaging Mission

To support the above mission objectives, a single imaging radiometer concept known as the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) has been selected. This concept, while yielding significant development/recurrent cost savings, allows the

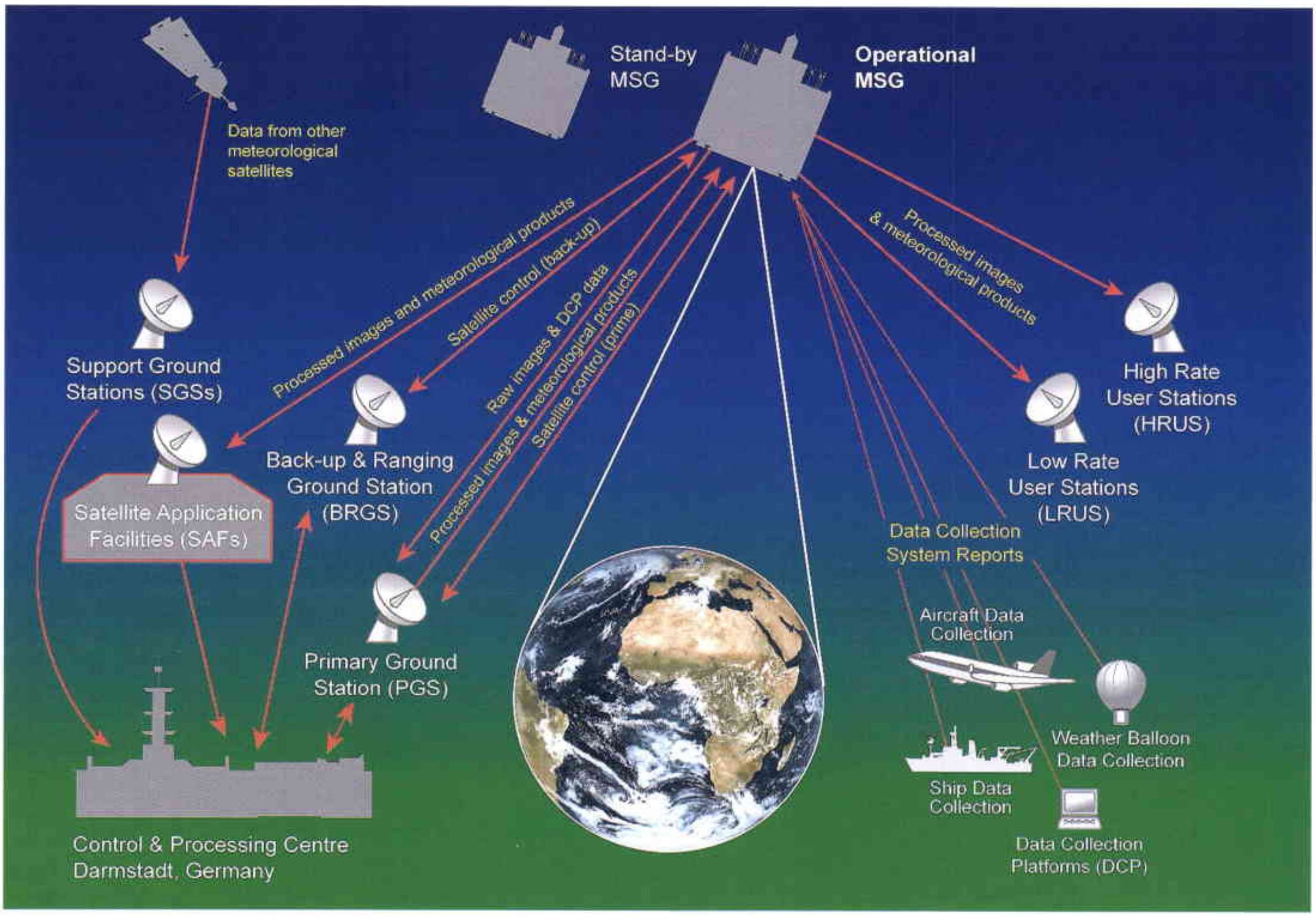


Figure 1. The MSG System configuration

simultaneous operation of all of the radiometer channels with the same sampling distance. It therefore provides the users with improved image accuracy and such products as atmospheric motion vectors and surface temperature, and also new types of information on atmospheric stability. Moreover, as the channels selected for MSG are similar to those of the AVHRR instrument currently being flown on polar-orbiting spacecraft, the efficiency of the global system will be increased due to the synergy of the polar and geostationary orbit data.

An outline of the overall mission and performance evolution from first- to second-generation Meteosat is given in Figure 2.

The imaging mission provides continuous imaging of the Earth in the 12 spectral channels of the SEVIRI instrument, with a baseline repeat cycle of 15 min. The calibration of the infrared cold-channel radiometric drift can be performed every 15 min, using an internal black-body calibration unit. The imager provides data from the full image area in all channels, except for the high-resolution visible channel, where the scanning mode can be switched by telecommand from the normal to an alternative mode (Fig. 3).

The VIS 0.6, VIS 0.8, IR 1.6, IR 3.9, IR 10.8 and IR 12.0 channels correspond to the six AVHRR-3 channels on-board the NOAA satellites, while the HRV, WV 6.2, IR 10.8 and IR 12.0 channels correspond to the first- generation Meteosat VIS, WV and IR channels (Fig. 4). The following so-called 'split-channel pairs' provide similar radiometric information and may therefore be used interchangeably: VIS 0.6 & VIS 0.8, IR 1.6 & IR 3.9, WV 6.2 & WV 7.3, and IR 10.8 & IR 12.0.

The HRV channel will provide high-resolution images in the visible spectrum, which can be used to support nowcasting and very-short-range forecasting applications.

The two channels in the visible spectrum, VIS 0.6 and VIS 0.8, will provide cloud and land-surface imagery during daytime. The wavelengths that have been chosen allow the discrimination from the Earth's surface of different cloud types, as well as discrimination between vegetated and non-vegetated surfaces. These two channels also support the determination of the atmospheric aerosol content.

The IR 1.6 channel can be used to distinguish low-level clouds from snow surfaces and supports the IR 3.9 and IR 8.7 channels in discriminating between ice and water clouds. Together with the VIS 0.6 and VIS 0.8 channels, the IR 1.6 channel may also support the determination of aerosol optical depth and soil moisture.

The IR 3.9 channel can be utilised to detect fog and low-level clouds at night, and to discriminate between water clouds and ice surfaces during daytime. The IR 3.9 channel may also support the IR 10.8 and IR 12.0 channels in the determination of surface temperatures by estimating the tropospheric water-vapour absorption.

The two channels in the water-vapour absorption band, WV 6.2 and WV 7.3, will provide the water-vapour distribution for two distinct layers in the troposphere. These two channels can also be used to derive atmospheric motion vectors in cloud-free areas, and will support the IR 10.8 and IR 12.0 channels in the height assignment of semi-transparent clouds.

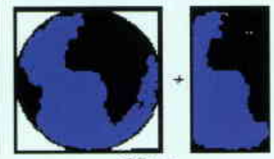
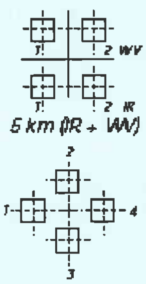
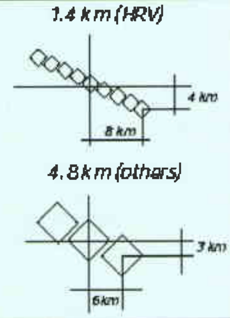
The IR 8.7 channel may also be utilised for cloud detection and can support the IR 1.6 and IR 3.9 channels in discriminating between ice clouds and the Earth's surface. Moreover, the IR 8.7 channel may also be applied together with the IR 10.8 and IR 12.0 channels to determine the cloud phase.

The SEVIRI channel that covers the very strong fundamental vibration band of ozone at 9.6 microns, namely IR 9.7, will be used to determine the total ozone content of the atmosphere and may also be applied to monitor the altitude of the tropopause.

The two channels in the atmospheric window, IR 10.8 and IR 12.0, will mainly be used together with the IR 3.9 channel to determine surface temperatures.

The IR 13.4 channel covers one wing of the fundamental vibration band of carbon dioxide

IMAGING/PSEUDO SOUNDING MISSION

		MOP	MSG
Imaging Format			
Imaging cycle		30 mn	15 mn
Channels		Wavelength	
	Visible	0.5 - 0.9	HRV VIS 0.6 VIS 0.8 IR 1.6
	Water Vapour	WV 6.4	WV 6.2 WV 7.3
	IR window	IR 11.5	IR 3.8 IR 8.7 IR 10.8 IR 12.0
	Pseudo sounding		IR 9.7 IR 13.4
Sampling distance		2.25 km (Visible) 4.5 km (IR + WV)	1 KM (HRV) 3 KM (others)
Pixel size		2.25 km (Visible) 5 km (IR + WV) 	1.4 km (HRV) 4.8 km (others) 
Number of detectors		4	42
Telescope diameter		400 mm	500 mm
scan principe		scanning telescope	Scan mirror

DATA CIRCULATION MISSION

	MOP	MSG
Transmission raw data rate	0.333 Mb/s	3.2 Mb/s
Disseminated image	0.166 Mb/s	1 Mb/s
Transmission burst mode	2.65 Mb/s	Search & Rescue package

Figure 2. Mission evolution from first- to second-generation Meteosat

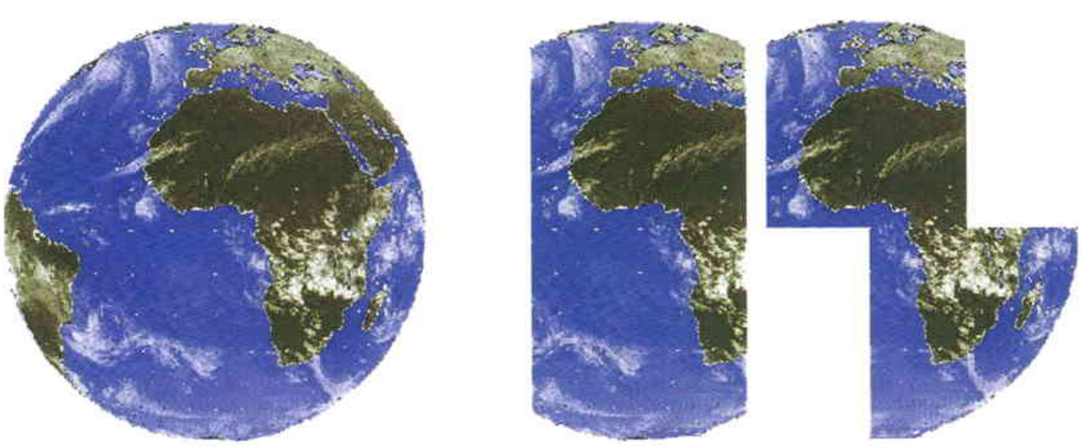


Figure 3. SEVIRI Earth-imaging frames: full image area, HRV channel normal mode and alternative mode

at 15 microns, and will therefore mainly be used for atmospheric-temperature sounding in support of air-mass instability estimation.

The Product-Extraction Mission
This mission will provide meteorological, geophysical and oceanographic Level 2.0 products from SEVIRI Level 1.5 imagery. It will continue the product-extraction mission of the current Meteosat system, and also provide additional new products.

The MSG meteorological products will be delivered to the user community in near-real-time via the Global Telecommunications System (GTS) or via the satellite's own High-Rate Image Transmission (HRIT) and Low-Rate Image Transmission (LRIT) schemes.

The Data-Collection and Relay Mission
The data-collection and relay mission will collect and relay environmental data from the automated Data Collection Platforms (DCPs) via the satellite. It will be a follow-on from the current Meteosat Data Collection Mission, with some modifications:
- increased number of international DCP channels
- increased number of regional channels
- DCP retransmission in near-real-time via the LRIT link
- some of the regional channels will operate at a higher transmission rate.

The Dissemination Mission
The dissemination mission will provide digital image data and meteorological products via two distinct transmission channels:
- the HRIT scheme transmits the full volume of processed image data in compressed form
- the LRIT scheme transmits a reduced set of processed image data and other meteorological data.

Both transmission schemes will use the same radio frequencies as the current Meteosat system, but the coding, modulation scheme, data rate and data formats will be different. Different levels of access to the high- and low-rate information transmission data will be provided to different groups of users through encryption.

The Meteorological Data Distribution mission of the current Meteosat System will be integrated into the HRIT and LRIT missions of MSG.

Figure 4. The spectral characteristics of the SEVIRI channels

Channel	Absorption Band Channel Type	Nom. Centre Wavelength (µm)	Spectral Bandwith (µm)	Radiometric Noise - Assessed for MSG-1 at End of Life at Reference Targets
HRV	Visible High Resolution	nom. 0.75	0.6 to 0.9	0.63 at 1.3 W/(m²·sr·µm)
VIS 0.6	VNIR Core Imager	0.635	0.56 to 0.71	0.27 at 5.3 W/(m²·sr·µm)
VIS 0.8	VNIR Core Imager	0.81	0.74 to 0.88	0.21 at 3.6 W/(m²·sr·µm)
IR 1.6	VNIR Core Imager	1.64	1.50 to 1.78	0.07 at 0.75 W/(m²·sr·µm)
IR 3.9	IR / Window Core Imager	3.92	3.48 to 4.36	0.17 K at 300 K
WV 6.2	Water Vapour Core Imager	6.25	5.35 to 7.15	0.21 K at 250 K
WV 7.3	Water Vapour Pseudo-Sounding	7.35	6.85 to 7.85	0.12 K at 250 K
IR 8.7	IR / Window Core Imager	8.70	8.30 to 9.10	0.10 K at 300 K
IR 9.7	IR / Ozone Pseudo-sounding	9.66	9.38 to 9.94	0.29 K at 255 K
IR 10.8	IR / Window Core Imager	10.80	9.80 to 11.80	0.11 K at 300 K
IR 12.0	IR / Window Core Imager	12.00	11.00 to 13.00	0.15 K at 300 K
IR 13.4	IR / Carbon Diox. Pseudo-Sounding	13.40	12.40 to 14.40	0.37 K at 270 K

The Geostationary Earth Radiation Budget (GERB) experiment
The GERB payload is a scanning radiometer with two broadband channels, one covering the solar spectrum, the other covering the entire electromagnetic spectrum. Data will be calibrated onboard the satellite to support the retrieval of radiative fluxes of reflected solar radiation and emitted thermal radiation at the top of the atmosphere with an accuracy of 1%.

The Geostationary Search and Rescue (GEOSAR) relay mission
The satellite carries a small communications payload to relay distress signals from 406 MHz beacons to a central reception station in Europe, which will pass the signals on for the rapid organisation of rescue activities. GEOSAR will thereby allow continuous monitoring of the Earth's disc and hence the issuing of immediate alerts. esa

MSG's SEVIRI Instrument

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The MSG satellite's main payload is the optical imaging radiometer, the so-called Spinning Enhanced Visible and Infrared Imager (SEVIRI). With its 12 spectral channels, SEVIRI will provide 20 times more information than the current Meteosat satellites, offering new and, in some cases, unique capabilities for cloud imaging and tracking, fog detection, measurement of the Earth-surface and cloud-top temperatures, tracking of ozone patterns, as well as many other improved measurements. The SEVIRI instrument has been manufactured by European industry under the leadership of Astrium SAS in Toulouse, France.

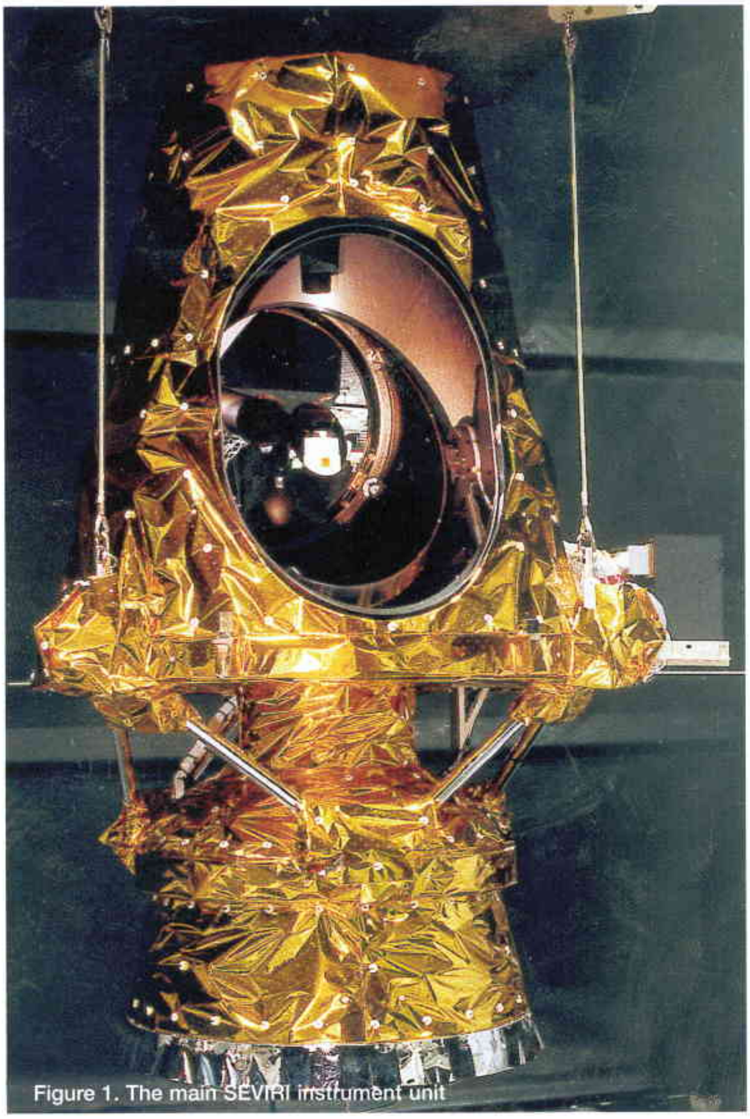

Figure 1. The main SEVIRI instrument unit

The instrument design

SEVIRI is a 50 cm-diameter aperture, line-by-line scanning radiometer, which provides image data in four Visible and Near-InfraRed (VNIR) channels and eight InfraRed (IR) channels. A key feature of this imaging instrument (Fig. 1) is its continuous imaging of the Earth in 12 spectral channels with a baseline repeat cycle of 15 min. The imaging sampling distance is 3 km at the sub-satellite point for standard channels, and down to 1 km for the High Resolution Visible (HRV) channel. The main characteristics of the instrument are summarised in Table 1.

The SEVIRI instrument is composed of a Telescope and Scan Assembly (TSA), a Focal Plane and Cooler Assembly (FPCA), and an Electronic Unit Assembly (EUA) (Figs. 2 & 3). The EUA, which controls SEVIRI and processes its data, consists of three electronics boxes located on the satellite main platform, namely the Functional Control Unit (FCU) and the Detection Electronics (DE), consisting of the Main Detection Unit (MDU) and the Preamplifier

Table 1. SEVIRI instrument characteristics

Spectral range:
- 0.4 – 1.6 μm (4 visible/NIR channels)
- 3.9 – 13.4 μm (8 IR channels)

Resolution from 35 800 km altitude:
- 1 km for the high-resolution visible channel
- 3 km for the infra-red and the 3 other visible channels

Focal plane cooled to 85/95 K
One image every 15 min
245 000 images over 7 yr nominal lifetime
Instrument mass: 260 kg

Dimensions:
- 2.43 m high
- 1 m diameter without Sun Shield

Power consumption: 150 W
Data rate: 3.26 Mbit/s

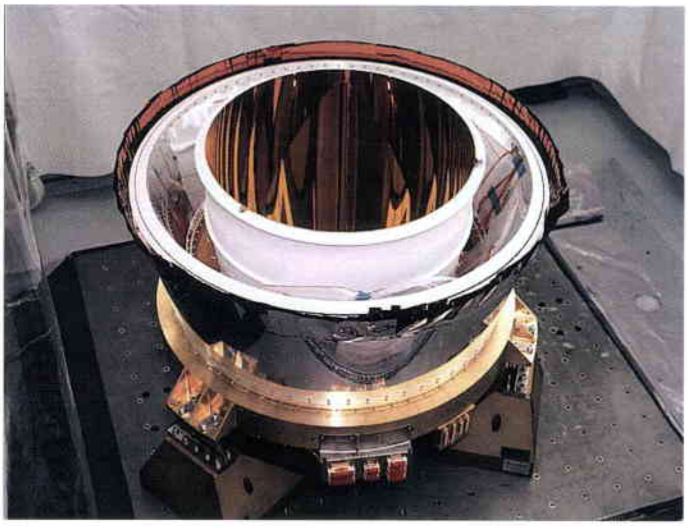

Figure 2. The SEVIRI radiator assembly

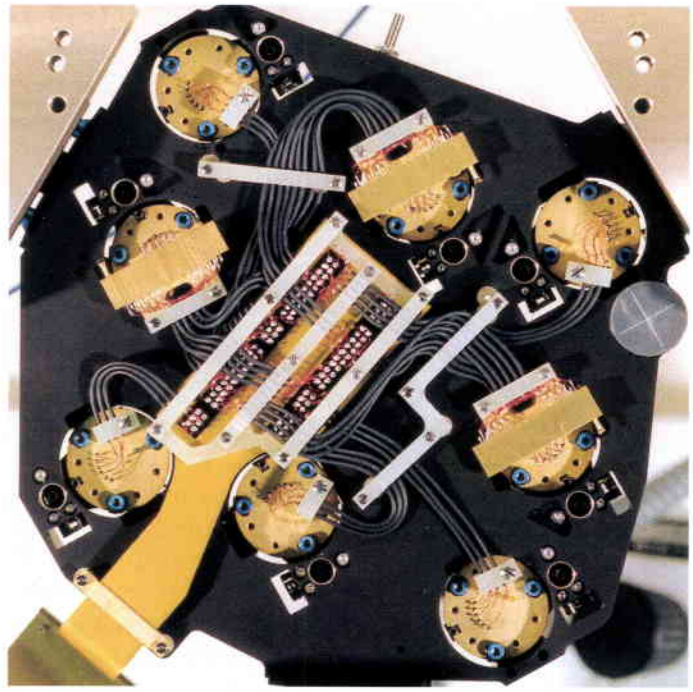

Figure 3. The SEVIRI cold-IR Optical Bench

Unit (PU). The FCU is responsible for SEVIRI's command and control, and it interfaces with the spacecraft's onboard data-handling subsystem.

The 12 SEVIRI channels consist of 8 InfraRed (IR) detector packages (3 detectors each), and 1 High Resolution in the Visible (HRV) channel (9 detectors), 2 Visible and 1 Near-IR (3 detectors each). The IR detectors are all made of mercury cadmium telluride, the visible detectors are in silicon and the NIR detectors are made from indium-doped gallium arsenide. The detectors are shaped and sized to satisfy both the radiometric and imaging performances required by the end users.

The operating principle

The scanning mirror is used to move the instrument line-of-sight (LOS) in the south-north direction. The target radiance is collected by the telescope and focused onto the detectors. Channel separation is performed at telescope focal-plane level, by means of folding mirrors. A flip-flop type mechanism is periodically actuated to place the IR calibration reference source in the instrument's field of view. The image data are directly transferred from the Main Detection Unit (MDU) to the onboard data-handling subsystem. The FCU controls the SEVIRI functions and provides the telemetry and telecommand interfaces with the satellite.

The Earth imaging is achieved by means of a bi-dimensional Earth scan, relying on the spacecraft's spin and the scanning mirror, as shown in Figure 4. The rapid scan (line scan) is performed from east to west thanks to the spacecraft's rotation around its spin axis (spin rate 100 rpm). The spin axis is perpendicular to the orbital plane and is nominally oriented in the south-north direction. The slow scan is performed from south to north by means of a scanning mechanism, which rotates the scan mirror in steps of 125.8 microradians. A total scan range of ±5.5° (corresponding to 1527 scanning lines) is used to cover the 22° Earth imaging range in the south-north direction, and 1249 scan lines to cover the whole Earth in the baseline repeat cycle.

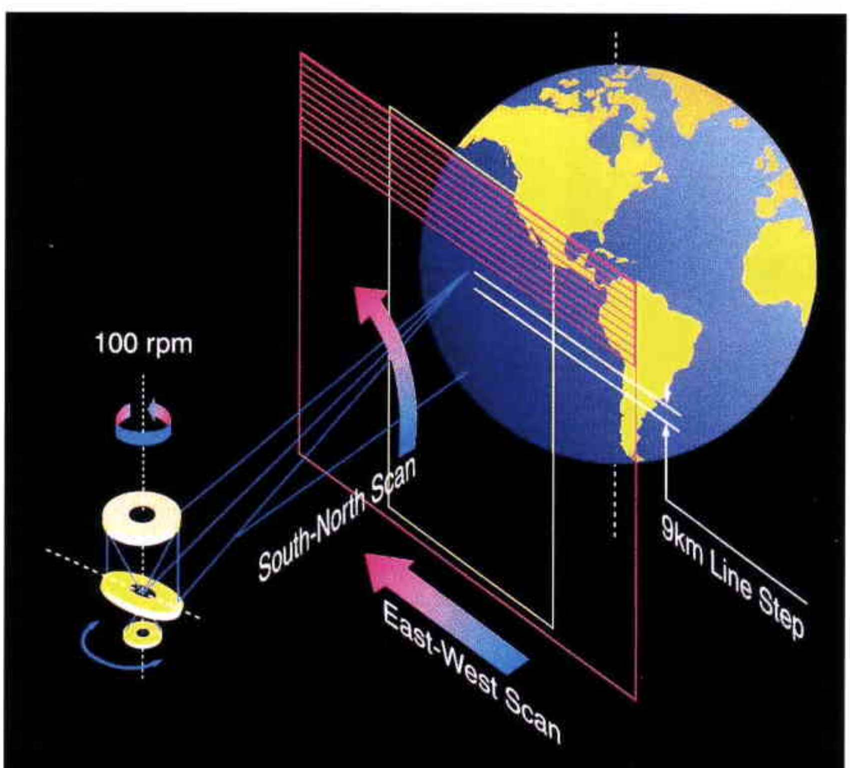

Figure 4. The SEVIRI instrument's mechanical scanning principle

The full Earth's disc image is obtained in about 12 min. The scanning mirror is then driven back to its initial position and the flip-flop mechanism is activated to insert the black body onboard the spacecraft into the optical path for the instrument calibration. The black body is removed from the calibration position after about 2 sec and Earth observation is resumed, leading to an overall repeat cycle of 15 min.

Performance verification

Radiometric performance

Characterisation of the SEVIRI instrument's radiometric performance centres on the determination of such parameters as the radiance response and its associated non-linearities, validation of the on-board calibration process, and the measurement of radiometric noise and drift. Constant and uniform targets are employed, as specified at system level.

The image data mean value (corresponding to one line) consists of samples coded over 10 bits, ranging from 0 to 1023. This results in up to 5751 samples for each HRV chain and 3834 samples for each of the other detection chains. A set of data is defined as the concatenation of the data lines corresponding to several consecutive Earth-acquisition windows, and corresponding to the same configuration (i.e. same illumination level and same detection-chain parameter settings). For all of the radiometric test results (spectral response, radiance response and noise), there are negligible differences between the operational temperatures of the IR focal plane at 85 K and 95 K. The MSG-1 environmental tests indicated that SEVIRI IR calibration is needed in the worst case once per nine images.

Imaging performance

Two major imaging-characteristic tests have been performed at SEVIRI and satellite level, addressing:
- the geometric imaging: checks were performed mostly in the ambient environment to determine the stability of SEVIRI's line of sight before and after environmental testing (e.g. thermal-vacuum and vibration)
- the Spatial Frequency Response (SFR): Modulation Transfer Function (MTF), sampling-distance and co-registration tests were performed in thermal vacuum.

The Central Line Of Sight (CLOS) instability due to thermo-elastic distortion of the radiometer is the most important contributor to geometric imaging errors. It was measured in vacuum for two extreme telescope temperatures during SEVIRI's thermal-vacuum testing. These measurements were used for instrument geometric performance verification whilst validating the thermo-elastic model. The results have shown the SEVIRI instrument to be stable in terms of both its line of sight and its overall geometric parameters.

The two-fold objectives of the SFR determination were to provide:
- on-ground characterisation allowing the SEVIRI Radiometer/Imager MTF to be determined
- on-ground measurements for the verification and characterisation of the SEVIRI co-registration error (including its internal IFOV sampling accuracy, i.e. pixel positions).

All of the MTF data were within specification, with sufficient margins to accommodate measurement errors and focus evolution during the instrument's in-orbit lifetime. HRV is the most sensitive channel, but with a defocussing of up to 2.8 mm it still meets the specifications. The instrument's stability has been fully demonstrated for all specified environments.

Conclusion

This article has described the SEVIRI instrument's design and the environmental testing approach applied to assess the flight model's performance for the MSG-1 satellite. The tests that have been performed have shown that the instrument meets the performance requirements for all specified environments and is therefore fully flight-qualified.

Acknowledgements

The author would like to thank the entire MSG/SEVIRI team, from ESA, Alcatel Space Industries and Matra Marconi Space, for their support and contributions to the analyses and testing. Special thanks go also to all of the engineers who have contributed to the development of the SEVIRI Imaging Radiometer.

MSG's GERB Instrument

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The Geostationary Earth Radiation Budget experiment (GERB), selected as an Announcement of Opportunity instrument for MSG, will make accurate Earth-radiation-budget measurements from geostationary orbit. The GERB instrument (and its recurrent models) has been designed, developed and manufactured by an International Consortium* led by the Rutherford Appleton Laboratory (RAL).

* Consortium members: Imperial College of Science, Technology and Medicine (ICSTM), London; Leicester University, UK; AEA Technology, UK; Galileo Avionica, Italy; Amos, Belgium and the Royal Meteorological Office (RMIB), Belgium.

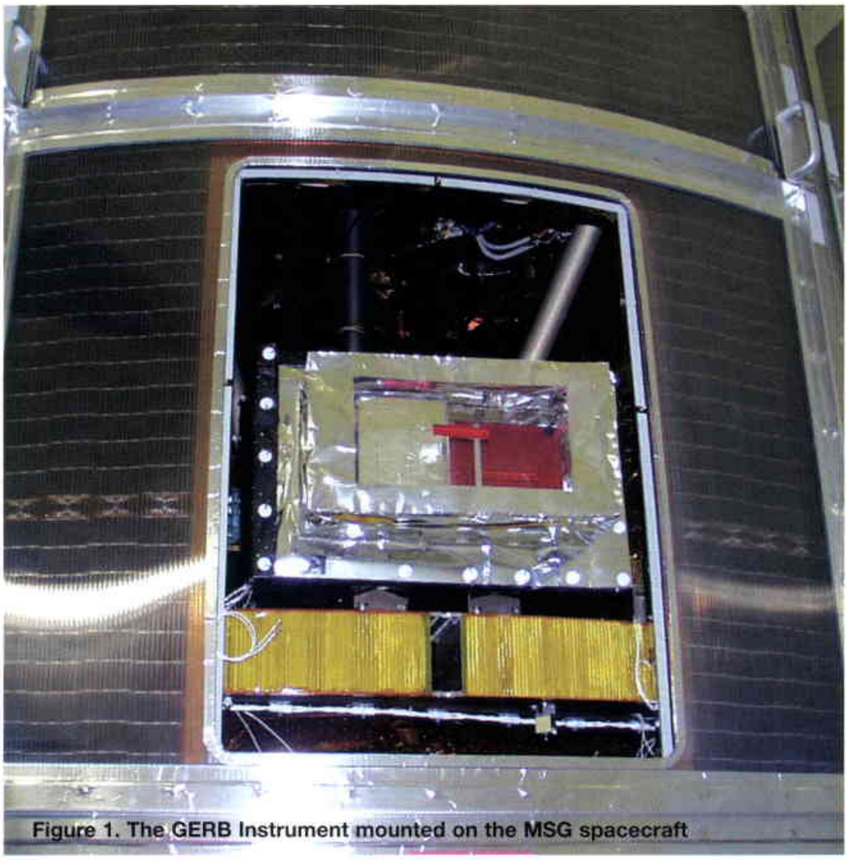

Figure 1. The GERB Instrument mounted on the MSG spacecraft

Introduction

The GERB instrument is a highly accurate visible-infrared radiometer, which will provide unique measurements of the outgoing short-wave and long-wave components of the Earth's radiation budget from geostationary orbit, which have not been achieved previously (Fig. 1). To date, all such measurements have been made from satellites in low Earth orbit (LEO). The data obtained from single satellites must be used with caution, as they cannot provide proper temporal sampling. In response to the diurnal variation in the solar heating, there are strong diurnal variations in the radiation budget observed, particularly over land. In order to provide coverage of the diurnal cycle with a temporal resolution of 3 h, four LEO satellites would be needed. However, at least hourly measurements are needed to resolve the diurnal cycle of tropical convection properly, and no practical system of polar orbiting or other LEO satellites can deliver this. The GERB instrument will provide a full Earth-disc image every 15 min, which will allow excellent temporal sampling.

Scientific goals

The overall GERB scientific aims can be summarised as:
- investigation of the role of clouds in the Earth's radiation budget and cloud radiative feedback
- investigation of the role of water vapour in radiative feedback
- observational studies of specific processes, such as tropical convection and marine strato-cumulus formation, and their diurnal and synoptic variability
- identification of additional constraints on numerical weather-prediction models
- improvement of LEO diurnal-variation simulation models and surface bi-directional reflectance functions
- validation of climate models for the MSG-observed regions
- contribution to a global Earth-radiation-budget measuring system by combining GERB data with that from other sensors (e.g. LEO satellites, CERES and ScaRaB), and
- synergy with SEVIRI short-wave visible calibration.

The GERB measurements will provide substantial contributions in each of these areas, leading to improved operational weather

Perfomancecharacteristics of the GERB instrument

Wavebands	Total Short wave (SW) Long wave (LW)	0.32 – 30 µm 0.32 – 4 µm 4 – 30 µm
Radiometry	**SW**	**LW**
Absolute Accuracy Signal/Noise Ratio Dynamic Range	<1% 1250 0 – 380 W.m^{-2}ster^{-1}	<0.5% 400 0 – 90 W.m^{-2}ster^{-1}
Spatial Sampling	45 x 40 km^2 (NS x EW) at nadir	
Temporal Sampling	15 min SW and LW fluxes	
Cycle Time	Full Earth disc, both channels in 5 min	
Co-Registration	Spatial: 3 km w.r.t. SEVIRI at satellite subpoint Temporal: within 15 min of SEVIRI at each pixel	
Instrument Mass	25 kg	
Power	35 W	

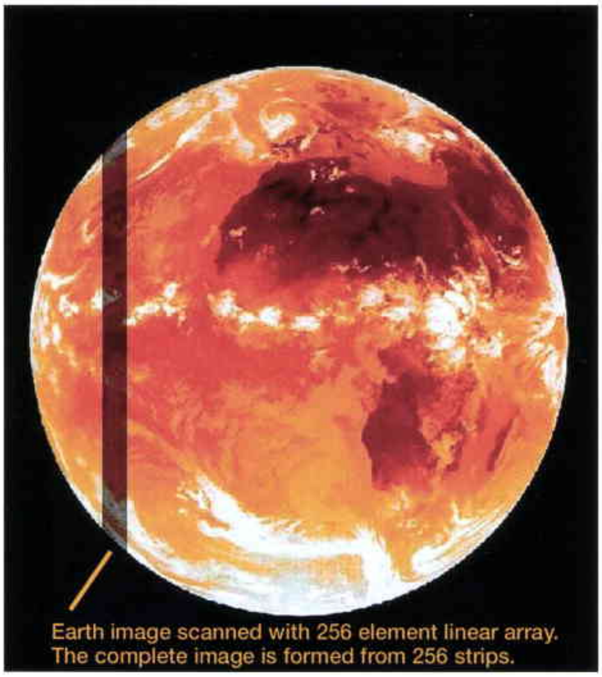

Figure 2. The Earth as observed by GERB (18° x 18°).

monitoring and permitting further important progress in climate-change research. Both short-wave (0.32 - 4 micron) and total (0.32 - 30 micron) radiance measurements will be made, with long-wave (4 - 30 micron) data obtained by subtraction. The accuracy requirements (1% short wave and 0.5% long wave) are an improvement over previous radiation-budget measurements. The Earth's radiation is detected by a thermoelastic detector array (bolometer) of 1 x 256 pixels, designed to image the full Earth's disc (18° field-of-view) in a north-south direction (Fig. 2). The exposure time to the Earth's radiation is limited to 40 ms within an MSG rotation. Full coverage of the Earth is achieved by scanning the detector' field of view continuously from west to east and back again, thereby building an image from a series of consecutive strips in the north-south direction. Three raw measurement samples covering the same scene (full Earth's disc) will be taken within a 15 min interval and averaged to bring the radiometric noise of the corresponding processed radiance within limits.

Instrument design

The highly autonomous GERB instrument consists of two main units:

The Instrument Optical Unit (IOU) which is very compact (56 x 35 x 33 cm^3), and includes essentially (Figs. 3 and 4):

- a telescope (three-mirror anastigmatic system)
- a de-scanning mirror for staring at appropriate targets, continuously rotating at 50 rpm in the opposite direction to the satellite's rotation (100 rpm), freezing the view of the Earth for a period of 40 ms

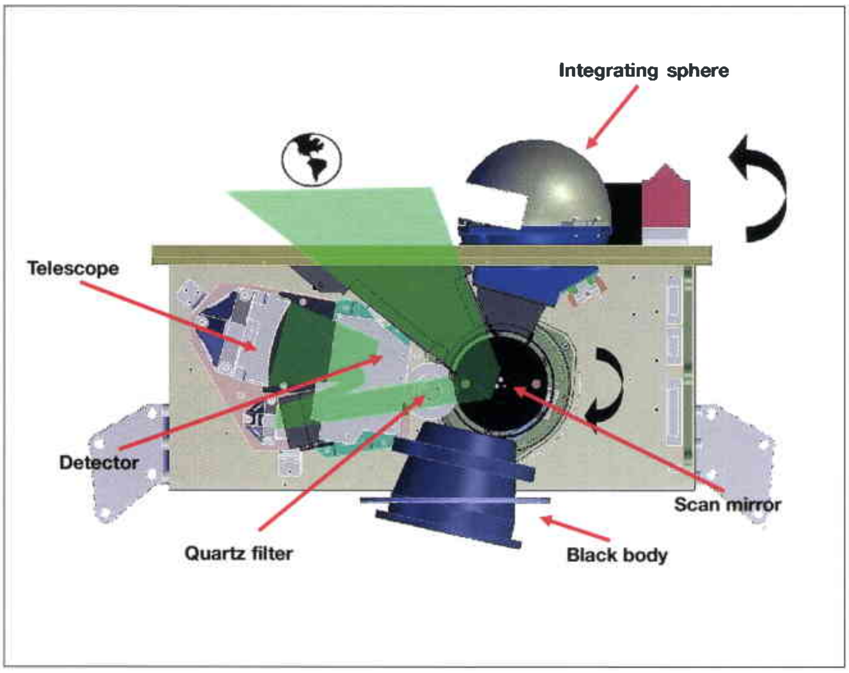

Figure 3. Schematic of the GERB Instrument Optical Unit (IOU)

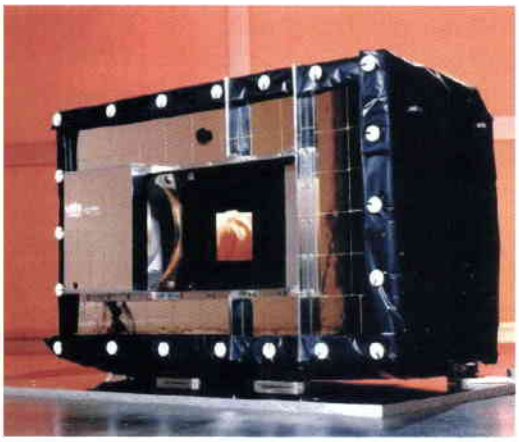

Figure 4. The GERB IOU flight unit

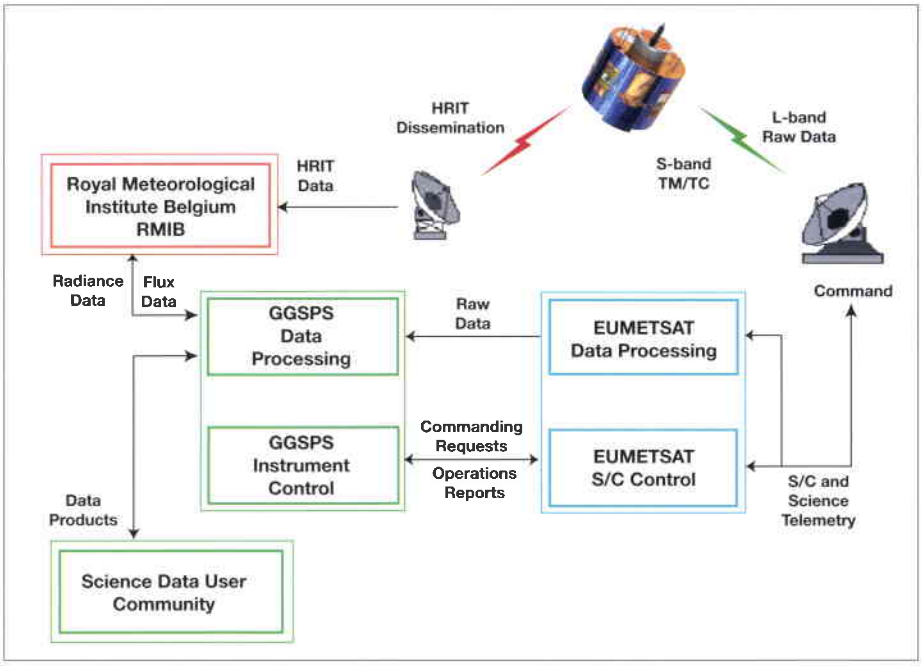

Figure 5. GERB data-processing scheme

- a wideband detector array (a linear, blackened, 256-element thermo-electric array) with its own signal-amplification and processing circuitry (including ASICs and a DSP)
- a quartz-filter mechanism used to switch the measurement into alternative wavebands (total and short-wave)
- calibration devices: a black-body for thermal calibration and a solar diffuser for monitoring the degradation of the short-wave reflectance of the mirrors, quartz-filter transmittance and detector absorption
- a passive thermal design, and
- a structure based on a solid-optical-bench design.

The Instrument Electronic Unit (22 x 27 x 25 cm^3) is designed to receive detector data, format them and pass them on to the spacecraft's data-handling system. It also provides regulated power to all of the subsystems, the thermal control of the IOU, and the command and data interfaces and the instrument monitoring and control functions.

Instrument calibration

GERB-1 has been exhaustively tested in a purpose-built calibration facility consisting of a vacuum chamber with a black body at about 300 K, which represents an Earth-like source (Warm Black Body, WBB), a black body at liquid-nitrogen temperatures as an approximation of the cold space (Cold Black Body, CBB), and an integrating sphere for calibration in the solar spectral domain. Radiometric data (gain, filter transmission, linearity, etc.), spectral responses at several discrete wavelengths, Point Spread Functions (PSF), and on-board black body performance have been measured. Checks for stray light and for gain drift as a function of temperature have also been made.

Data analysis and its comparison with unit-level measurements and instrument-level predictions has demonstrated the validity of the GERB concept.

Apart from the on-ground calibration, extensive in-orbit calibration campaigns will be carried out throughout instrument's in-orbit lifetime. A variety of targets such as the Moon and reference sites on the Earth will be used to derive proper instrument performances.

In-orbit operation and data processing

Once in orbit, the GERB instrument's operation will be monitored by a team at RAL and ICSTM. In addition, a number of satellite parameters will be monitored at Eumetsat to provide a basic check on the safety of the instrument. The processing of the GERB data will be divided between two locations (Fig. 5). The conversion of raw GERB data to calibrated geo-located radiances will be done at RAL using software of the GERB Ground Segment Processing System (GGSPS). The processed data will then be passed to RMIB for conversion to fluxes. RMIB will make certain flux products available via the World Wide Web for short-term usage, but the main GERB data and product archive for long-term usage will be at RAL.

Several of the planned scientific studies are expected to take advantage of the synergy between the GERB and SEVIRI (see companion article in this Bulletin) instruments and their data. From the merging of the two data streams, near-real-time estimates of the Earth's radiation budget with the high spatial resolution of SEVIRI (3 km at nadir) can be anticipated. It is expected that once the scientific community realises the full potential of GERB as a result of the GERB-1 flight, there will be a growing demand for its measurements and processed data.

Acknowledgement

Funding for the first GERB instrument has been provided by the National Environment Research Council (NERC) of the United Kingdom, Services Federaux des Affaires Scientifiques, Techniques et Culturelles (SSTC) of Belgium, and Agenzia Spaziale Italiana (ASI) of Italy. The recurrent models for MSG-2 and -3 are being financed by Eumetsat.

MSG's Communications Payload

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The highly reliable communications system needed for data transmission and distribution for the mission is provided by the MSG Communications Payload (MCP) carried on the spacecraft. It consists of three main elements, namely the Antenna Subsystem, the MCP Transponder, and the TTC Transponder.

The Antenna Subsystem

The MSG telecommunications system has to provide a number of mission-critical services, each of which requires a particular type of antenna:

- Reception of telecommands and transmission of housekeeping data: the S-band transponder is responsible for this task and is connected to a dedicated telemetry, tracking and command (TTC) antenna.
- Transmission of the measured radiometer (SEVIRI) data, coming from the data-handling subsystem, to the primary ground station: the Electronically Despun Antenna (EDA) used for this task operates at L-band.
- Reception of pre-processed images with associated data: a Toroidal Pattern Antenna (TPA) operating at S-band is used for this task.
- Transmission to users: this relies on the L-band EDA antenna for low-resolution and high-resolution data.
- Reception data from Data Collection Platforms (DCPs): this requires an electronically switched circular array antenna and uses the UHF EDA operating at 402 MHz.
- Transmission of the DCP data: this is provided by the L-band EDA antenna.
- Reception of emergency (Search & Rescue): this relies on the UHF EDA operating at 406 MHz.
- Transmission of Search & Rescue messages: this is provided by the L-band EDA antenna.

Figure 1 shows the flight-model MSG Antenna Subsystem.

The S-band TTC antenna is a low-gain, wide-coverage antenna, the design of which has been optimised for MSG, taking into account the spacecraft's much larger body compared to the previous Meteosat satellite series.

The Toroidal L- and S-band antennas are narrow-band, reduced-height, slotted-wave-

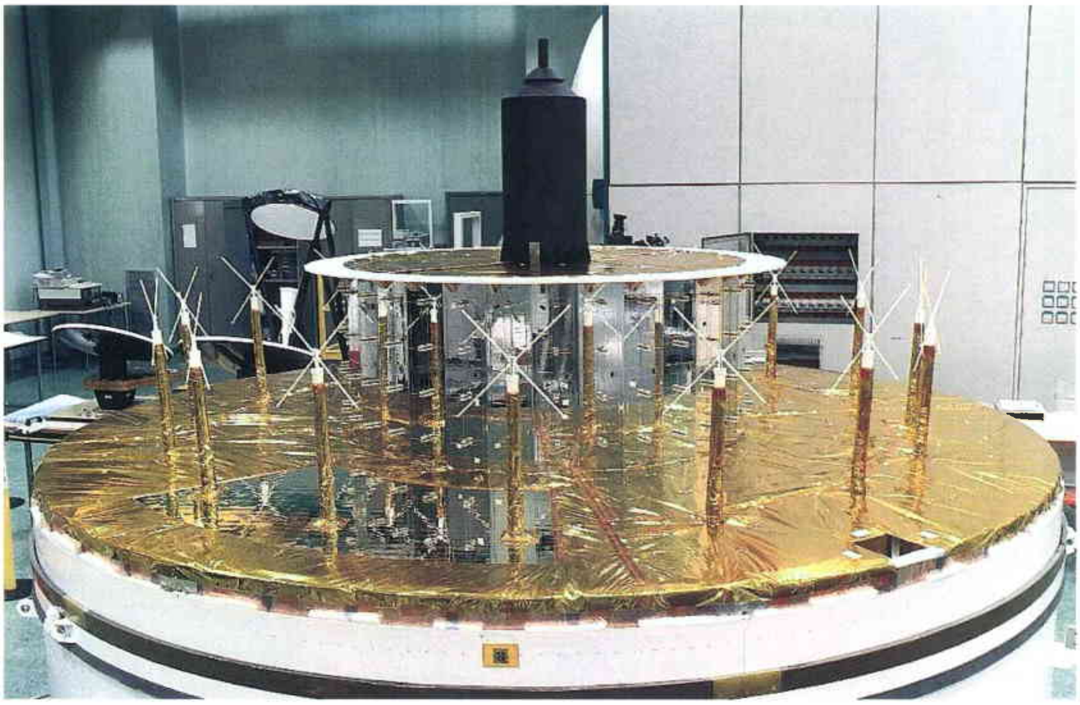


Figure 1. The flight-model MCP Antenna Subsystem

guide antennas, which provide toroidal patterns in the plane perpendicular to the satellite spin axis.

The L-band EDA is used in transmit mode only, to send the raw image data to the primary ground station and the processed data, received via the S-band link, to the secondary users. As the satellite rotates at 100 rpm and the high-gain antenna beam needs to be aimed continuously at the ground, an electronic means of despinning this beam in the opposite direction to the satellite's rotation is implemented. This antenna is composed of 32 columns of 4 dipoles each, and is mounted on a cylindrical construction close to the top of the satellite.

The UHF-band EDA is used to receive the meteorological data from the DCPs operating in the UHF band and the newly implemented Search & Rescue mission on MSG. An electronically switched UHF array of 16 crossed dipoles has been selected for the purpose. Of the 16 dipoles, four are used to form the beam, whereby the next dipole is selected every 22.5° synchronised with the satellite's spin rate.

To control and supply all of the complex timed switching for the various active elements of the antenna subsystem, a dedicated piece of equipment known as the Common Antenna Control Electronics (CACE) is used. It receives synchronisation signals from the Data Handling Subsystem and generates the correctly timed drive signals for the Antenna Subsystem.

The MCP Transponder Subsystem

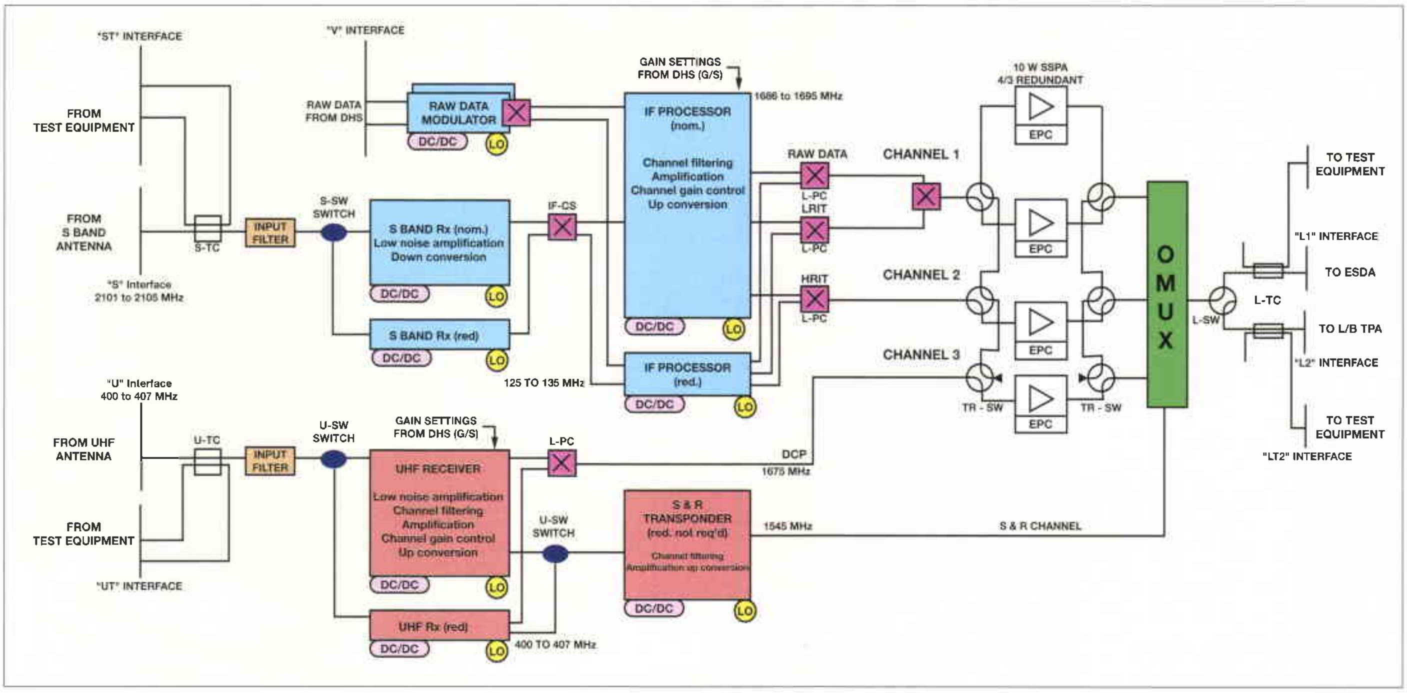
The MCP Transponder Subsystem's tasks on-board the satellite are the reception, amplification and transmission of the following channels:

- Raw Data Channel: down-linking to the Primary Ground Station (PGS) of the SEVIRI (and GERB when applicable) raw data stream, plus auxiliary/ancillary information received from the Data Handling Sub-system.
- HRIT Channel: high-data-rate dissemination to the user community (High-Rate User Stations, or HRUSs) of processed meteo-rological data and images received from the PGS.
- LRIT Channel: low-data-rate dissemination to the user community (Low-Rate User Stations, or LRUSs) of processed meteo-rological data and images received from the PGS.
- DCP Channel: relay of messages from the Data Collection Platforms to the PGS for further distribution.
- Search & Rescue Channel: relay of distress signals from emergency beacons on the visible Earth's disc to dedicated ground stations (Cospas/SarSat network).

Figure 2 gives a block diagram of the MCP, and Figure 3 is a photograph of the first flight transponder during integration.

The raw data signal coming from the Data Handling Subsystem is fed to the Raw Data Modulator (internally redundant), which performs the QPSK (quaternary phase-shift keying) modulation before the data enters the Intermediate Frequency Processor (IFP). The IFP also receives the HRIT and LRIT signals coming from the S-band antenna via the

Figure 2. Block diagram of the MSG Communications Payload (MCP)



S-band filter and the S-band receiver (two in cold redundancy), which provide the necessary low-noise amplification and frequency down-conversion. The IFP equipment, which operates in cold redundancy, filters and up-converts the three signals separately and amplifies them to a selected output level or with a certain fixed received-signal (RD, HRIT and LRIT) gain set by ground command. The output signals of the IFP drive the Solid-State Power Amplifiers (SSPAs) directly to their chosen operating points.

The multi-carrier DCP channel, which can be composed of up to 460 individual carriers, enters the transponder together with the Search & Rescue signal via the UHF filter and feeds the two UHF receivers (configured in cold redundancy). They perform the low-noise amplification and frequency up-conversion to the corresponding down-link frequency in L-band. The DCP signal is then forwarded to the SSPA matrix for further amplification.

The SSPA matrix is composed of four SSPAs (output power about 10 W per amplifier) in a 4:3 redundancy scheme. One SSPA is allocated to the HRIT channel, one is used by the RD and LRIT channels simultaneously, and one is dedicated to the DCP channel. The remaining redundant SSPA can be used by any of the other channels in the event of a failure.

The Search & Rescue signal is pre-amplified by the UHF receiver and then further filtered, frequency up-converted and power-amplified in the Search & Rescue Transponder.

After power amplification, all of the channels (RD+LRIT, HRIT, DCP and S&R) are filtered and combined in the output multiplexer (OMUX), before being fed to the Antenna Subsystem.

The TTC Transponder Subsystem
The Telemetry, Tracking and Command (TTC) Subsystem consists of two S-band transponders and it performs the following functions:

- Reception and demodulation of the up-link command and ranging subcarriers of the S-band signal transmitted by the ground control station.
- Delivery of the telecommand video signal to the on-board Data Handling Subsystem.
- Modulation of the down-link carrier by the received and demodulated ranging signal and the telemetry signals received from the on-board Data Handling Subsystem.
- Power amplification and delivery of the S-band down-link carrier to the Antenna Sub-system.

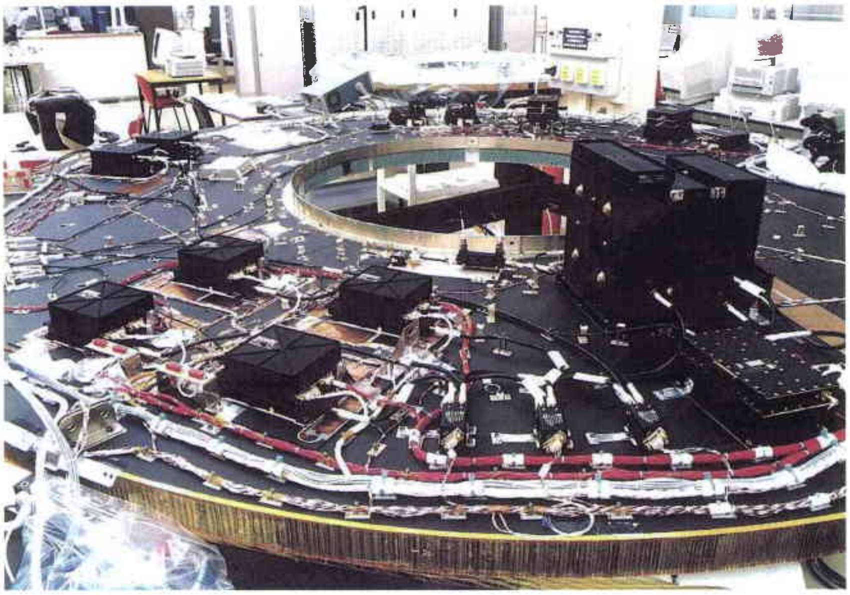


Figure 3. Integration of the first flight-model MCP Transponder

The down-link carrier can be generated coherently or non-coherently with respect to the up-link carrier received from the ground station.

The TTC Subsystem is composed of two identical transponders, each consisting of several modules packaged in a single unit (Fig. 4). The receiver and transmitter of each transponder are electrically independent, except for the necessary interconnections to perform the ranging operations. The receivers and the transponders will always be 'on' throughout the satellite's lifetime, with the transmitters operated in cold redundancy. esa

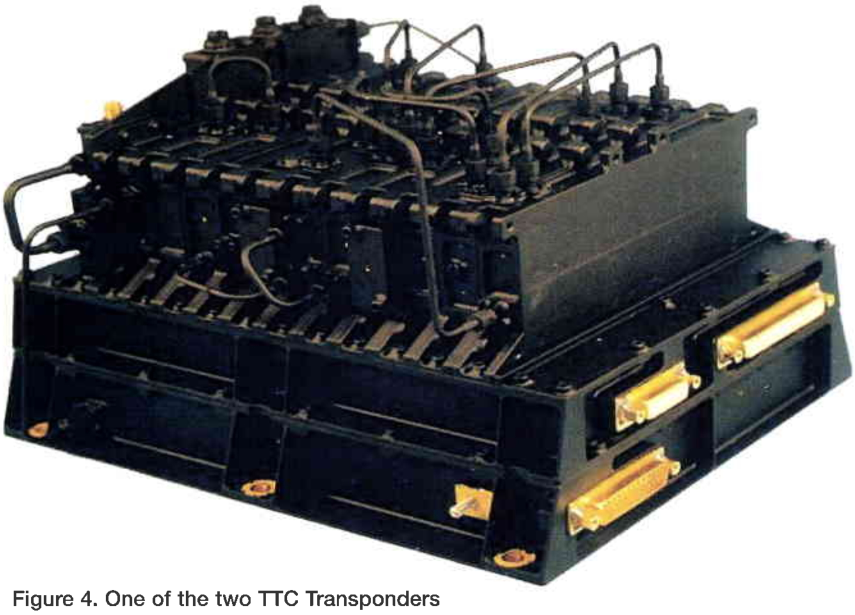


Figure 4. One of the two TTC Transponders

Figure 1. The launch of MSG on 28 August 2002

MSG-1 Safely in Orbit

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Almost exactly 25 years after the launch of the very first ESA-developed Meteosat spacecraft in November 1977, the first representative of the next generation of European weather satellites has been successfully placed in orbit by Europe's own Ariane launcher and is currently being made ready to add new dimensions to the monitoring of our planet's fragile climate.

Initially, the first of the next generation of European weather satellite's, MSG-1, was slated for launch in October 2000, but delays incurred in the ground segment's development resulted in the launch being postponed until August 2002. As a consequence, MSG-1 was put into storage from early 2001 until August 2001. During this storage period, work proceeded in industry on the two recurrent satellite models MSG-2 and MSG-3, and the meteorological services continued to use data from two of the Meteosat first-generation satellites, which are still performing satisfactorily and are planned to be operational for a few more years yet.

In the meantime, the August 2002 launch date was confirmed, and an Ariane-5 launcher selected (with a co-passenger), after a shock-qualification problem had been resolved by the inclusion of three shock-absorbing devices in the launcher/spacecraft interface. Consent to ship MSG-1 to the Ariane launch site in French Guiana was subsequently given by both ESA and Eumetsat, and on 14 May 2002 the satellite was on its way. Figure 2 shows the satellite container emerging from the Antonov transport aircraft in Rochambeau, close to Cayenne in French Guiana, the following day.

After transport by truck from Rochambeau to the Guiana Space Centre (CSG) in Kourou, the spacecraft was put into the launch site's clean room (S1) for final assembly and checkout, which was completed at the end of June. The spacecraft was subsequently transported to one of the fuel filling areas, before being combined with its co-passenger Atlantic Bird-1, an Alenia-built spacecraft that will be operated

Figure 2. The MSG satellite container emerging from the Antonov transport aircraft in French Guiana

Figure 3. The arrival of MSG in the clean room at the Guiana Space Centre (CSG)

by Eutelsat, prior to being lifted onto the top of the Ariane-5 launcher.

At the same time as the spacecraft's arrival (Fig. 3), the ESA team responsible for supervising the pre-launch activities, a team from Alcatel Space the contractor who built the spacecraft and would conduct the final pre-launch testing, and a Eumetsat team responsible for the provision of the launch services, also arrived at CSG to prepare for the launch.

In parallel, ESA's European Space Operations Centre (ESOC) in Darmstadt (D), which is responsible for the mission's Launch and Early Orbit Phase (LEOP) under a contract from Eumetsat, began an extensive simulation programme in preparation for operating the spacecraft after its separation from the launcher.

After a one-day delay due to a minor ground-control problem, at 19.45 h local time (22.45 h GMT) on 28 August the Ariane-5 launcher carrying MSG-1 lifted-off from the Guiana Space Centre and successfully delivered this improved Meteosat, and its payload companion Atlantic Bird-1, into Geostationary Transfer Orbit (GTO), with a flawless launch. Under ESOC's control, MSG-1 will now make a series of manoeuvres using its onboard propulsion system, which will carry it onwards to its definitive geostationary operating orbit in a few weeks' time.

Eumetsat, as the satellite's commercial operator, will be taking over MSG-1 at the end of September, following the in-orbit check-out of its systems, and will then proceed with acceptance of the payload. The first image from the satellite is expected by the end of October. About a year after launch, MSG-1 will commence operational service above the equator, at 0° longitude, taking over from Meteosat-7 as the main weather- and climate-monitoring satellite for Europe.

MSG-1 is to be followed by two other identical satellites, for which Eumetsat will be fully responsible. MSG-2 is currently scheduled for launch in early 2005, and MSG-3 in spring 2009. Since each satellite has a nominal operational lifetime of seven years (two more than the current Meteosats), the new family of spacecraft will provide a cost-effective system that will allow Europe to maintain its leading role in gathering global weather data until at least 2012. Consideration is being given to building a fourth satellite to maintain continuity of the programme beyond 2014.

Following the success of the launch from Kourou, José Achache, ESA Director of Earth Observation, told the Press: *"With the World's political leaders gathered in Johannesburg to discuss the requirements for sustainable global development of our planet, ESA is proud to have deployed this satellite on behalf of Eumetsat and for the benefit of countless users. It is going to improve weather forecasting, our understanding of climate change and the issue of the planet's water resources".*

GMES

– Un instrument de gouvernance environnementale pour l'Europe

J. Achache
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Le 15 juillet 2002, ESA et la Commission européenne ont lancé une procédure de consultation sur l'initiative de surveillance mondiale pour l'environnement et la sécurité (GMES). En combinant les technologies spatiales, terrestres et aéroportées, l'initiative GMES a pour objectif de mieux exploiter les capacités et infrastructures actuelles et futures de l'Europe et d'améliorer les mécanismes de collecte et de distribution de l'information. GMES répondra donc au souci croissant des responsables politiques d'accéder librement, en temps utile et en toute indépendance aux informations sur l'environnement et la sécurité aux niveaux mondial, régional et local. Il apportera un soutien aux politiques de l'Union européenne dans des domaines tels que le développement durable, le changement climatique à l'échelle planétaire, et la politique étrangère et de sécurité commune.

Sécurité environnementale

A l'aube du 21ème siècle, les questions d'environnement et de sécurité prennent une place chaque jour plus importante dans les préoccupations quotidiennes des citoyens. Elles sont désormais en première ligne de l'agenda politique. Environnement et sécurité doivent être entendus ici au sens le plus large. Il s'agit bien sûr, en premier lieu, de la sécurité des biens et des personnes contre les agressions et les vols. Mais ces préoccupations expriment aussi un besoin accru de sécurité sanitaire devant l'émergence des maladies virales, sida et hépatites, et des maladies à prion et devant la recrudescence des maladies infectieuses; un besoin, également, de sécurité alimentaire après les récentes épidémies de fièvre aphteuse et de vache folle et face aux discours confus entretenus sur les OGM; un besoin, encore, de sécurité civile face aux catastrophes naturelles, inondations, tempêtes et séismes, aux risques industriels, pollutions, incendies et explosions; un besoin, enfin, d'assurance face aux incertitudes sur les conséquences du réchauffement de la planète. Ainsi, le contrôle des épidémies, la préservation de l'intégrité des ressources alimentaires, de la qualité de l'eau, la prévention des catastrophes et la prévision des changements climatiques sont les enjeux de ce que l'on appelle aujourd'hui la sécurité environnementale.

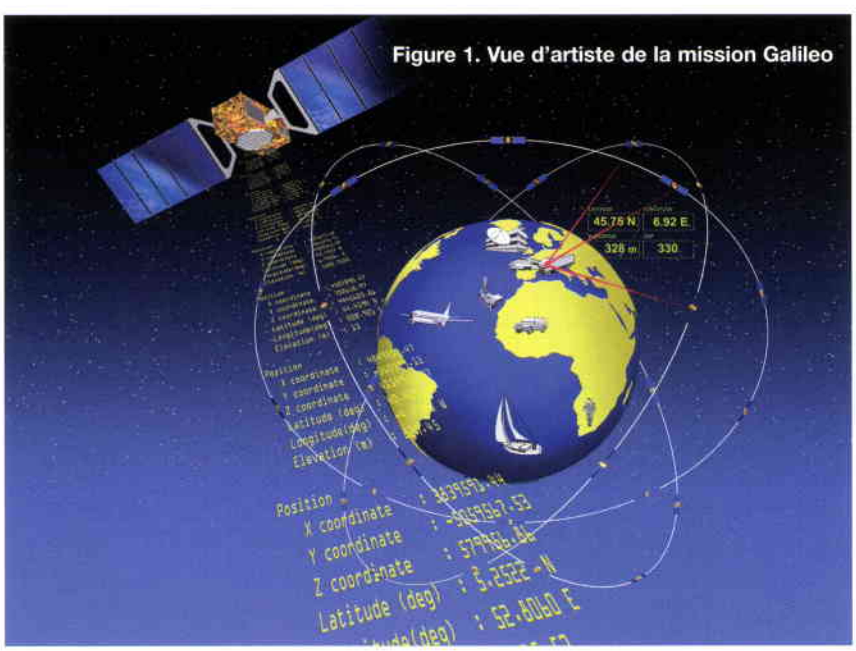


Figure 1. Vue d'artiste de la mission Galileo

Cette question de la sécurité a pris, avec les événements du 11 septembre et les agressions bactériologiques qui ont suivi, un tour infiniment plus tragique et plus urgent. Depuis ces attentats, chacun s'interroge sur les moyens de lutter contre de tels actes terroristes et, plus généralement, sur les moyens d'assurer la sécurité des populations. Les agences spatiales ne peuvent se tenir à l'écart d'un tel questionnement. Les satellites d'observation et les systèmes d'écoute électronique sont déjà utilisés par les agences de renseignement dans la surveillance des activités terroristes. On prévoit que demain les systèmes spatiaux de positionnement comme le GPS et Galileo permettront d'améliorer la sécurité dans les avions et au voisinage des aéroports ou encore de suivre à la trace tous les transports de matière dangereuse, sur terre et sur mer.

Au delà, ces événements apportent un éclairage nouveau sur la réflexion engagée en Europe autour du programme GMES de surveillance globale pour l'environnement et la

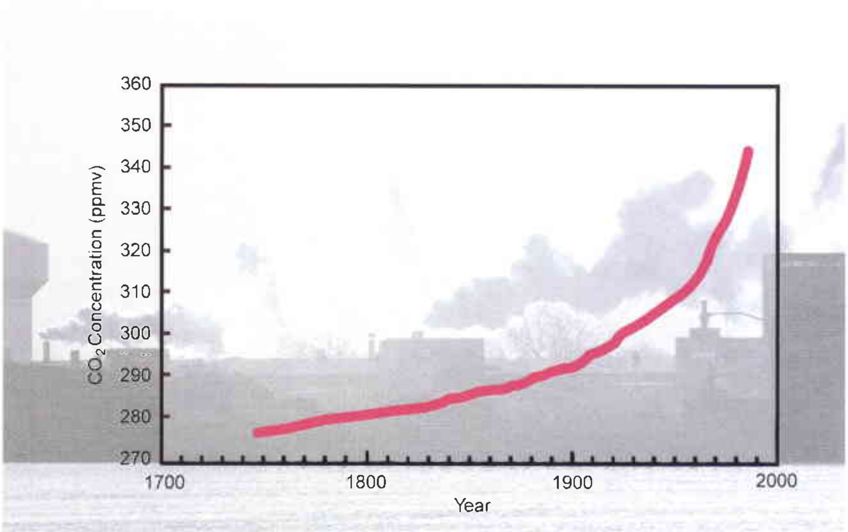


Figure 2. Concentrations de dioxyde de carbone dans l'atmosphère de la Terre depuis les dernières 250 années.

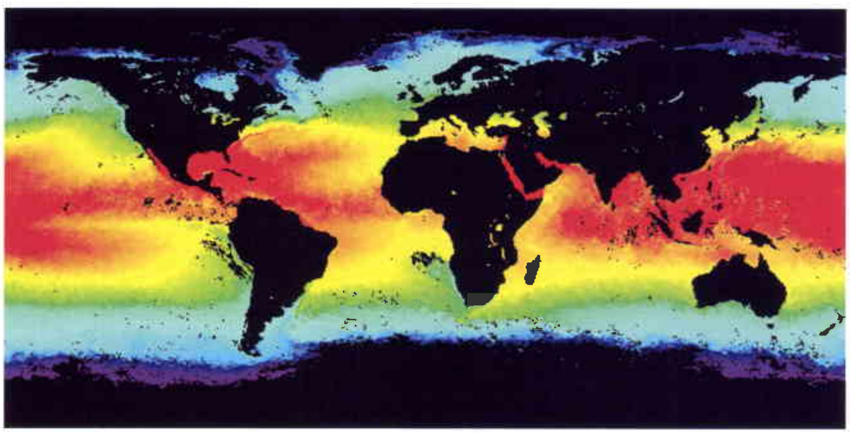


Figure 3. Températures globales de surface de la mer (SST) qui seront surveillées par l'instrument AATSR d'Envisat (source: RAL, GB)

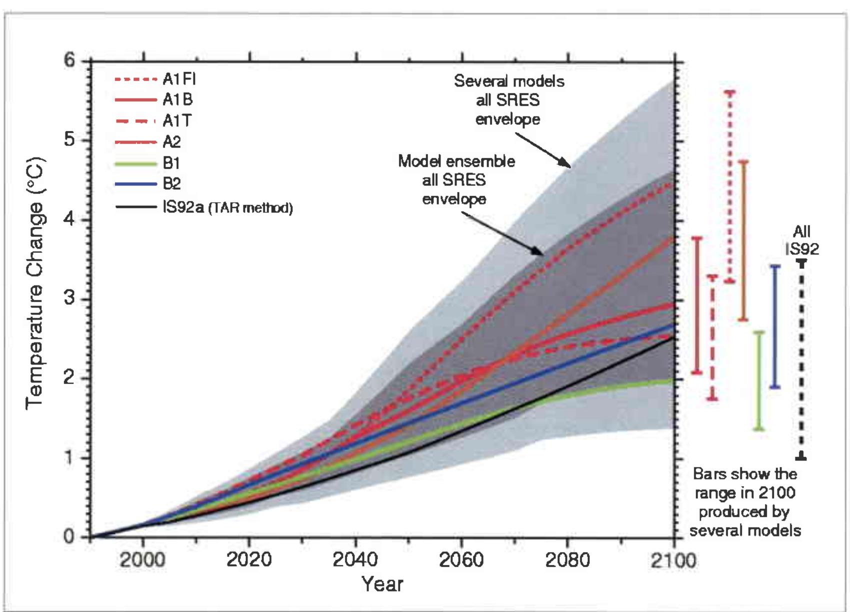


Figure 4. La prévision de changements de température pendant le XXIe siècle grâce aux différents scénarios d'émission (de SRES, 2000) et modèles de climat (de IPCC, 2001)

sécurité. Les menaces que font peser les conséquences de l'effet de serre et des changements climatiques ne sont pas du même ordre que la menace terroriste même si, dans les deux cas, la sécurité des populations est en jeu. Pourtant, nous sommes confrontés là à deux menaces de nature fondamentalement globale auxquelles on ne peut opposer qu'une réponse collective et globale. Ni les responsabilités, ni les causes, ni les conséquences des changements climatiques globaux ne sont et ne seront également partagées. Pourtant, nous sommes collectivement concernés et nous serons tous affectés, à des degrés divers. Face à l'effet de serre, la réponse ne peut pas être simplement technologique. Comme face au terrorisme, la lutte contre les changements climatiques sera longue et se conduira sur plusieurs fronts, scientifique, économique et politique. Aucun bouclier spatial ne nous protégera durablement contre l'une ou l'autre de ces menaces. Mais les techniques spatiales peuvent être bien davantage qu'un simple bouclier. Elles permettent d'observer, de mesurer, de surveiller et de transmettre. Elles peuvent ainsi constituer le cœur d'un système global d''intelligence environnementale' capable de modéliser, comprendre et prévoir l'évolution de notre planète.

En renonçant à ratifier le protocole de Kyoto, les Etats-Unis ont-ils pris la mesure de la menace que constitue le réchauffement de la planète pour notre civilisation et la sécurité des populations? Ils semblent avoir fait le choix d'adapter leurs modes de production et leur modèle économique aux contraintes du changement climatique avant que celui-ci ne soit devenu insupportable et surtout irréversible. Dans cette hypothèse aussi, le besoin de surveiller, de comprendre et de prévoir est essentiel.

C'est tout l'enjeu du programme GMES.

Le siècle de la diplomatie environnementale

En juillet 2001 à Berlin, 188 états ont reconnu ensemble les dangers d'un réchauffement planétaire et ratifié le protocole de Kyoto. Le dernier rapport de l'Intergovermental Panel on Climate Change (IPCC) est en effet catégorique sur plusieurs points. La température moyenne de l'atmosphère a augmenté (de 0,6°C) depuis un siècle. La composition chimique de l'atmosphère, et en particulier la teneur en gaz à effet de serre, a changé et l'activité humaine en est la cause. Enfin, si rien n'est fait pour réduire les émissions de ces gaz à effet de serre, la température moyenne sur la planète va augmenter d'ici la fin du siècle de 1,4 à 5,8 °C selon les hypothèses utilisées. Pour mesurer l'ampleur de la menace que ce réchauffement constitue, songeons que le passage de la dernière ère glaciaire à la période tempérée que nous vivons s'est accompagné d'un réchauffement planétaire moyen de seulement 4°C. Les modèles actuels ne permettent pas de prédire avec précision les conséquences de ce réchauffement pour chaque région. Elles pourront être très variable d'une région à l'autre. Ainsi, les changements climatiques qui vont advenir produiront sécheresses et désertification pour les uns, inondations et tempêtes pour les autres. Peut-être verrons-nous aussi d'heureuses surprises comme ce 'Sahara vert' prévu par certains modèles. Par contre, ils indiquent tous des conditions climatiques plus instables et donc des perturbations et des événements extrêmes plus frequents. Les inondations qui se multiplient en Europe en sont peut-être une première indication. Elles montrent en tout cas à quel point notre civilisation est devenue sensible à toute variation, même faible, des conditions climatiques.

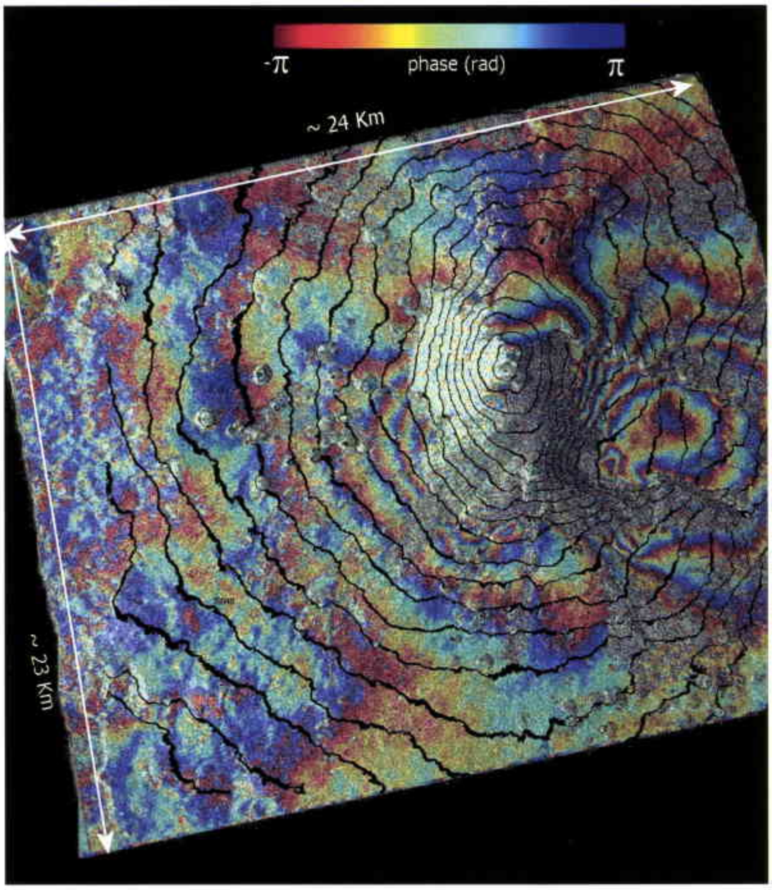


Figure 5. Carte interférométrique du mont Etna, en Italie, après l'éruption du volcan à l'été 2001, produite avec des données des satellites ERS

En effet, un premier constat s'impose: l'humanité est devenue plus vulnérable aux phénomènes naturels à mesure que les populations se sont regroupées dans de vastes zones urbaines. Ce sont aujourd'hui plus de 3 milliards d'êtres humains qui vivent dans des mégapoles et sont concentrés sur quelques pour-cent de la surface de la Terre, le long des fleuves, à proximité des grandes failles sismiques ou dans les régions côtières s'exposant ainsi aux inondations, aux ouragans et aux catastrophes telluriques.

Face à ces catastrophes naturelles, les enjeux sont autant humains qu'économiques. Combien de temps encore pourrons-nous tolérer que les catastrophes naturelles tuent autant qu'elles le font, en particulier les séismes: 25 000 morts en Turquie en 1999, 6000 à Kobe au Japon en 1995. Les inondations, si elles sont moins mortelles, entraînent aussi leur lot de dévastations dans les pays développés comme dans les pays en développement. Avec l'augmentation de la variabilité climatique, elles deviennent aussi plus fréquentes. Au plan économique, selon une étude récente d'une compagnie de réassurance, les catastrophes ont coûté plus de 100 milliards d'euros, pour la seule année 1999.

Un second constat est dressé dans le rapport de l'IPCC: l'Homme pèse sur son environnement, sur l'évolution du climat et sur les ressources naturelles. La question n'est plus de savoir si la quantité de carbone dans l'atmosphère va doubler mais à quelle vitesse et si nous serons préparés à faire face aux conséquences. L'Homme est devenu le premier facteur d'érosion sur Terre, bien avant le vent, la pluie et les fleuves et le principal agent de déforestation. En bouleversant ainsi le relief et la couverture végétale, il modifie profondément les équilibres naturels. Il prélève la majeure partie de l'eau douce utilisable à la surface des continents. Cette dégradation des

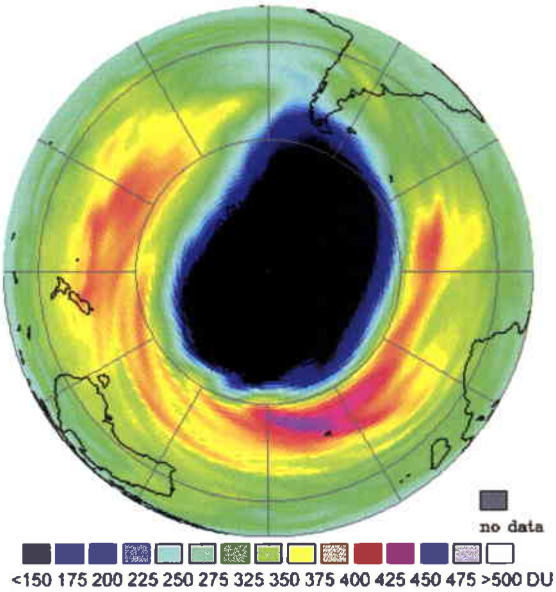


Figure 6. L'étendue du trou d'ozone au-dessus d'Antarctique le 22 septembre 2000, calculée à partir des données du satellite ERS-2 (source: KNMI, Pays-Bas)

milieux, cette raréfaction des ressources, la déforestation, la sécheresse, la pollution des eaux et des sols, contribuent à l'augmentation de la pression environnementale qui constitue une source croissante d'insécurité, d'instabilités et de conflits. Ces phénomènes sont aussi des causes de pathologies et d'affections nouvelles, qu'il s'agisse de maladies respiratoires dues à l'ozone et au dioxyde d'azote dans les grandes villes, de la recrudescence des épidémies de méningite en Afrique liées à l'augmentation des aérosols, conséquence de la désertification, ou encore de la réapparition de fièvres hémorragiques véhiculées par des insectes dans les régions tropicales.

Une réponse collective à l'échelle mondiale est en cours d'élaboration dans le cadre de conventions internationales impliquant tous les pays de la planète. Ce travail est engagé et la ratification récente du protocole de Kyoto, même en l'absence des Etats-Unis, est un signe encourageant. Et ce n'est pas le seul. Depuis le premier sommet de la Terre de Rio en 1992, ce sont plus de 200 traités, conventions et accords internationaux sur l'environnement, la limitation des produits toxiques, le partage des ressources naturelles ou encore la préservation d'espèces et de régions menacées qui ont vu le jour et sont en cours de négociation ou en attente de ratification. Les plus connus sont le protocole de Montréal sur les CFC et la couche d'ozone, les accords sur la biodiversité et la désertification et, bien sûr, le protocole de Kyoto sur les émissions de gaz à effet de serre.

Autour de ces négociations, tout un dispositif de 'diplomatie environnementale' rassemblant experts et politiques se met en place dans la plupart des pays pour préparer et négocier ces accords. L'enjeu en est la participation à l'élaboration des règles et des contours d'une gouvernance environnementale de la planète, la définition des modèles économiques et politiques du développement durable, les conditions de la croissance des pays du Sud et surtout, les règles de gestion et de partage des ressources naturelles, et tout particulièrement de l'eau. Sur toutes ces questions, la conduite de négociations internationales nécessite une bonne connaissance de l'état effectif de l'environnement et de son évolution et la compréhension des causes et des mécanismes des changements observés afin de pouvoir évaluer les conséquences environnementales, sociales et économiques des mesures envisagees. La mise en œuvre de ces traités et conventions lorsqu'elles sont établies, nécessite, quant à elle, de disposer de moyens de vérification et d'évaluation.

De l''Information dominance' à la 'Global transparency'

Quels peuvent être, vis-à-vis de ces enjeux, la place et le rôle des satellites?

Dans la négociation environnementale, comme dans toute négociation diplomatique, la maîtrise de l'information est déterminante. Durant toute la guerre froide, les affrontements diplomatiques entres grandes puissances se sont appuyés sur des services de renseignement puissants et organisés chargés de collecter et d'analyser toute information pertinente et de la mettre à la disposition des décideurs politiques et des négociateurs. Si l'essentiel de ces informations était d'abord collecté 'sur le terrain', dès la fin des années 60, les satellites ont démontré leur apport notable. Pour les Etats-Unis et l'Union Soviétique, ils ont rapidement constitué une source privilégiée de renseignement et les années 70 ont vu le déploiement de véritables constellations de satellites-espions, les 'Keyhole', 'Lacrosse' et 'Cosmos'.

Avec la chute du mur de Berlin, les enjeux de souveraineté se sont déplacés et les états ont cherché à asseoir leur présence économique en soutenant les ambitions internationales de leurs entreprises. La conquête des marchés et le contrôle de la production de marchandises a pris le pas sur la conquête des territoires et le contrôle des zones d'influence respectives. Les années 80-90, qui furent marquées notamment par l'Uruguay round, dernier round de négociation du GATT, qui a mis en place l'Organisation Mondiale du Commerce, ont alors vu l'émergence d'une diplomatie d'un nouveau genre, qu'on pourrait qualifier de 'diplomatie commerciale'. Dans cette course, la clé a encore été la capacité des différents acteurs à accéder à l'information et à en contrôler la diffusion, les Etats-Unis allant jusqu'à en faire une doctrine, celle de l''Information dominance'. Et là encore on retrouve, au cœur de cette doctrine, de puissants systèmes satellitaires comme le réseau Echelon', réseau planétaire d'écoute, de traitement et d'analyse des communications.

Les futures négociations environnementales obéiront à la même logique. Chaque intervenant doit pouvoir s'appuyer sur un dispositif d''intelligence environnementale' qui lui permette de surveiller, d'analyser, de comprendre et d'anticiper les changements de l'environnement, l'altération ou la raréfaction des ressources, les menaces que cela peut faire peser sur les populations et surtout d'évaluer les conséquences politiques, économiques, sociales et environnementales des choix qui seront faits. Dans cette nouvelle diplomatie environnementale, les états ne sont plus seuls autour de la table. La multiplicité des acteurs impliqués dans ces négociations, et notamment les organisations non gouvernementales et la communauté scientifique, crée une situation inédite et pose clairement la question de l'accès aux observations et aux télécommunications spatiales, au moins pour traiter des questions scientifiques et des problèmes liés au changement global et au développement durable. Pourra-t-on aboutir à davantage de transparence dans l'accès à l'information et tout particulièrement à l'information spatiale? C'est la question de la 'Transparence globale'.

Face aux catastrophes naturelles, il est urgent de disposer de systèmes intégrés de surveillance, de prévision et d'alerte capables de prévoir et de prévenir les effets des catastrophes et pas seulement d'en évaluer les dégâts. Plusieurs expériences en cours, et notamment la Charte Internationale sur les Catastrophes Naturelles mise en place par l'ESA, la France (CNES) et le Canada (ASC), auxquelles se sont joints récemment l'Inde (ISRO) et les USA (NOAA), ont fait la démonstration opérationnelle de l'apport des techniques spatiales pour la prévention, la prévision et la gestion des catastrophes. Ces expériences ont montré que la résolution des images, les délais d'obtention des informations et la permanence des systèmes de communication nécessaires dans ces situations pour évaluer les dégâts et conduire les opérations de secours se révèlent très proches des spécifications des systèmes militaires et de leurs contraintes opérationnelles. La prévision et la gestion des catastrophes naturelles posent ainsi le problème de l'utilisation à des fins civiles de systèmes d'observation militaire et, plus généralement, de l'utilisation duale des systèmes spatiaux (i.e. des systèmes capables de satisfaire conjointement des besoins civils et des besoins militaires). Là encore, l'alternative est posée: 'Information dominance' ou 'Global transparency'?

Construire un système de renseignement environnemental

GMES est un programme européen pour répondre à tous ces besoins. GMES, pour 'Global Monitoring for Environment and Security', est un programme conjoint de l'ESA et de la Commission européenne avec la participation des agences spatiales nationales, de l'industrie et de la communauté scientifique. L'objectif est de coordonner les programmes spatiaux et les systèmes non spatiaux dédiés à l'observation de la Terre et à l'étude de l'environnement avec les efforts de recherche et développement engagés par les états et la Commission européenne et les besoins de tous les utilisateurs potentiels, afin de constituer, à terme, un système complet d'aide à la décision, publique ou privée, capable d'acquérir, de traiter, d'interpréter et de diffuser toute information utile sur l'environnement, les risques et les ressources naturelles.

Observer, mesurer

Les techniques spatiales sont un outil idéal pour la surveillance globale, permanente et fiable de l'environnement, aussi bien de l'atmosphère, des océans que des terres émergées. Les données ainsi recueillies peuvent couvrir toutes les échelles nécessaires d'espace, du continent à la ville, jusqu'à l'habitation individuelle, et de temps, depuis la décennie pour suivre les changements du climat, jusqu'à l'heure pour anticiper les catastrophes naturelles, comme cela se fait déjà pour les cyclones tropicaux.

Toutefois, nous ne pouvons pas tout mesurer depuis l'espace. Beaucoup de paramètres essentiels doivent être mesurés dans l'atmosphère, au sol, dans le sous-sol ou dans les océans, en particulier les données chimiques et biologiques. C'est pourquoi un système d'information comme GMES, doit également s'appuyer sur des observations in situ de l'environnement. En cela, GMES est bien l'analogue environnemental des systèmes de renseignements traditionnels où observations et écoutes par satellites viennent compléter les informations obtenues sur le terrain.

Modéliser, comprendre

Mais les données spatiales brutes sont généralement peu utiles pour un utilisateur non spécialiste à la recherche d'informations pratiques et opérationnelles sur l'air, le sol, l'eau ou la végétation. Elles le sont encore moins pour un ministre ou un diplomate en charge de négocier un traité environnemental dans un champ de contraintes imposé par des considérations politiques et économiques. L'utilisation rationnelle des observations de l'environnement, leur transformation en information pertinente et utile pour le politique nécessitent un effort de décryptage et de traduction.

La décision politique et les choix diplomatiques doivent pouvoir se fonder sur la meilleure connaissance des phénomènes en jeu. La compréhension approfondie des processus est donc la priorité car nous souffrons d'un déficit de connaissance scientifique sur bon nombre de questions. En dépit des certitudes acquises récemment sur l'évolution de l'environnement et les causes des catastrophes naturelles, de nombreuses incertitudes demeurent. Réduire ces incertitudes demandera un effort soutenu pour améliorer les modèles dont nous disposons et acquérir des observations sur de longue durée nécessaires pour nourrir ces modèles. La mesure globale, continue et durable de l'environnement terrestre apparaît clairement comme l'objectif premier d'un système GMES tant l'évolution de l'environnement et de ses interactions avec la société ne peuvent être analysées et comprises qu'avec l'appui d'observations de longue durée. Celles-ci permettront d'identifier les processus responsables des dégradations lentes des ressources et de l'environnement global voire d'élaborer des modèles de prévision prenant simultanément en compte les processus naturels, les choix énergétiques, les choix industriels ou agricoles, les choix politiques d'aménagements et d'urbanisation et surtout les capacités d'évolution et les besoins des sociétés.

Réduire les incertitudes, prévoir et gérer la planète

En ce qui concerne les changements climatiques, les principales incertitudes portent actuellement sur le rôle des nuages et des aérosols, sur les échanges entre les océans et l'atmosphère, sur les sources et les puits de carbone, sur les conséquences des changements d'occupation des sols, sur le rôle des calottes polaires et surtout sur l'effet des couplages multiples qui interviennent dans le système climatique entre les différents polluants de l'atmosphère, entre l'évolution de la couche d'ozone et l'effet de serre. Le couplage entre les différentes échelles d'espace et de temps jouera également un rôle critique. Dans le domaine des catastrophes naturelles, des progrès encourageants ont été accomplis durant la dernière décennie mais beaucoup d'incertitudes demeurent, notamment sur les mécanismes de déclenchement de ces catastrophes, la réponse des milieux naturels et les effets de l'anthropisation sur ces deux processus.

GMES pourra bénéficier de l'expérience acquise dans le domaine de la prévision météorologique. L'exemple de la météorologie est, en effet, instructif à bien des égards. Les services météorologiques nationaux se sont développés avec les progrès des connaissances sur les processus atmosphériques et avec l'élaboration de modèles dynamiques globaux de l'atmosphère. Ils ont progressé encore récemment avec la compréhension du couplage entre l'océan et l'atmosphère. On peut observer qu'ils s'appuient, comme GMES le fera, à la fois sur des observatoires spatiaux, regroupés sous la responsabilité de l'organisation européenne Eumetsat, et sur des réseaux d'observatoires in situ.

Des capacités et des services analogues commencent à se mettre en place pour la prévision de l'état de la mer, en France avec le projet Mercator ou en Norvège avec le système Diadem/Topaze, deux projets qui s'inscrivent dans le cadre de l'expérience internationale GODAE. Là encore, la prévision opérationnelle s'appuie sur le triptyque observations spatiales/mesures in situ/modèles. GMES permettra d'étendre ces capacités au domaine des terres émergées. Or, dans ce domaine, l'homme interagit directement avec les processus naturels. C'est là un défi important de GMES: élaborer aussi bien des systèmes d'observation que des modèles d'évolution et de prévision qui prennent en compte simultanément les processus naturels, les activités industrielles et les besoins des sociétés.

La prévention, la prévision et la gestion des catastrophes en phase opérationnelle font partie des objectifs de GMES. Des efforts importants sont déjà engagés en Europe dans la prévention et la prévision des inondations à partir des observations spatiales et les premiers systèmes opérationnels se mettent en place auprès des sécurités civiles et des gestionnaires de bassins. Les progrès réalisés dans ce domaine doivent beaucoup à la coopération exemplaire des industriels, des sociétés de service, des centres de recherche publics et des administrations responsables. L'apport des images spatiales dans la gestion des situations de crise a été démontré à plusieurs reprises par les équipes de secours, les sécurités civiles et les organisations humanitaires lors de nombreux événements récents (ouragan et glissements de terrain au Salvador, inondations en France, séismes en Turquie et en Inde, éruption du Nyiragongo, etc.) notamment grâce à la Charte Internationale sur les Catastrophes Naturelles.

Les atouts de l'Europe

Le premier atout de l'Europe est l'existence de nombreux organismes de recherche qui travaillent sur la compréhension des changements climatiques, des risques naturels, des processus physiques impliqués dans l'évolution des milieux naturels et des enjeux sociologiques et politiques des changements globaux ou encore sur les outils mathématiques, numériques et informatiques adaptés à leur modélisation. Ces compétences peuvent être mobilisées au profit de GMES. Sur le thème du changement global, la coopération entre ces organismes est déjà bien établie à l'échelle européenne et mondiale à travers des programmes scientifiques internationaux comme l''International Geosphere-Biosphere Programme' (IGBP) et le 'World Climate Research Programme' (WCRP). Sur les autres thèmes, et notamment celui des catastrophes naturelles, il est encore nécessaire de renforcer la coopération entre tous les acteurs à l'échelle européenne.

En appui à ces efforts, des missions scientifiques exploratoires sont développées dans le cadre du programme 'Living Planet' de l'ESA, les missions Earth Explorer, ou dans un cadre national par les différentes agences en Europe, à l'image du microsatellite Demeter développé par le CNES pour les risques sismiques ou de la 'Disaster Monitoring Constellation' développée par l'Université de Surrey en Grande-Bretagne. A terme, les données fournies par l'ensemble des satellites des agences spatiales participant au partenariat international IGOS (International Global Observing Strategy) pourront contribuer aux travaux de démonstration de GMES, voire à la mise en œuvre opérationnelle de ce programme.

Le second atout de l'Europe est l'existence simultanée d'un réseau de services publics organisés à l'échelle de la communauté européenne (e.g. l'Agence européenne pour l'environnement), des états ou encore des régions et d'un important tissu de sociétés de service, notamment sur le marché de l'information géographique. Ces acteurs sont les mieux placés pour coordonner l'expression des besoins des individus, des collectivités, des entreprises et des administrations et relayer l'information fournie par un système GMES jusqu'à son destinataire final, dans la forme et dans les délais qui conviennent. Ces agents disposent en outre de réseaux d'observatoires in situ qui sont, nous l'avons déjà dit, une composante essentielle d'un système de renseignement comme GMES.

Enfin, l'Europe dispose déjà ou disposera bientôt de satellites qui permettent de traiter dès aujourd'hui plusieurs des questions qui relèvent de GMES. Toutefois, la majeure partie de ces satellites n'ont pas de caractère opérationnel et, de ce fait, ne répondent pas à l'exigence de continuité d'observation indispensable à un système de renseignement comme GMES: beaucoup sont des satellites expérimentaux destinés à la recherche ou à des opérations de démonstration. Seuls les satellites d'observation météorologique, exploités par Eumetsat (Meteosat, auxquels succéderont bientôt MSG - Meteosat Second Generation - et plus tard MetOp) et les satellites SPOT, dont le dernier, SPOT-5, vient d'être lancé, correspondent à ce critère. Les satellites canadiens RADARSAT, avec le prochain lancement de RADARSAT-2, répondront également à cette exigence.

L'océanographie spatiale devrait atteindre bientôt ce stade opérationnel. Cette discipline s'est développée avec Topex/Poseidon, un projet conjoint du CNES et de la NASA. Son plus grand titre de gloire est d'avoir permis d'élucider le phénomène El Niño. Plus généralement, la prise en compte de l'océan comme réservoir de chaleur, dans des modèles couplés de l'océan et de l'atmosphère, a ouvert la voie à la prévision climatique à moyen terme. On peut ainsi prévoir aujourd'hui le niveau moyen des précipitations sur de nombreuses régions du globe avec près de six mois d'avance et donc anticiper les risques éventuels de sécheresses ou d'inondations. On est bien là au cœur des ambitions de GMES. Avec le lancement de Jason, toujours en partenariat entre le CNES et la NASA, la continuité des mesures sera assurée pour quatre années supplémentaires. La surveillance globale des océans à des fins opérationnelles nécessitera d'assurer la pérennité de ces mesures au-delà de Jason. C'est l'objet d'un accord en cours de négociation entre le CNES, la NASA et les deux agences qui de part et d'autre de l'Atlantique mettent en œuvre les satellites météorologiques: Eumetsat et la NOAA.

Figure 9. Le satellite Envisat de l'ESA, lancé le 1er mars 2002

Les satellites radar ERS-1 et ERS-2 de l'ESA ont également fourni de longue séries de mesures, principalement en imagerie radar, en altimétrie océanique et sur l'état de la couche d'ozone, dont la pérennité est aujourd'hui assurée avec le lancement d'Envisat. Ce satellite permettra en outre d'expérimenter de nombreux autres instruments du système GMES pour le suivi de la chimie de l'atmosphère et du cycle du carbone et pour la prévision des catastrophes.

La continuité des mesures altimétriques fournies par Jason et ERS contribuera aussi à l'étude du cycle de l'eau continentale, à la surveillance des zones inondables et à la gestion prévisionnelle des ressources en eau. En effet, les satellites d'altimétrie permettent la mesure directe du niveau des grands lacs continentaux et des principaux fleuves. Demain, les missions CHAMP (financé par l'agence spatiale allemande, le DLR), GRACE (par la NASA et le DLR) et GOCE (par l'ESA) devraient aussi apporter leur contribution à ces problèmes, par la mesure fine des variations du champ de gravité qui reflètent les changements de niveau des nappes phréatiques. CryoSat, en mesurant l'évolution des calottes polaires, complètera l'étude du cycle de l'eau.

A terme, il appartiendra à GMES d'assurer la continuité opérationnelle de ces mesures, dès que leur utilité aura été confirmée par une communauté d'utilisateurs. Cette stratégie, où la continuité opérationnelle est mise en œuvre sur la base des résultats éprouvés de missions scientifiques expérimentales, est au cœur de la stratégie du programme Earth Watch de l'ESA qui cherchera, en outre, à assurer la meilleure complémentarité entre les programmes propres de l'ESA tel TerraSar, les initiatives nationales et bilatérales en Europe et celles des autres agences dans le monde, réduisant ainsi les duplications et permettant de couvrir au plus vite l'ensemble des besoins de GMES.

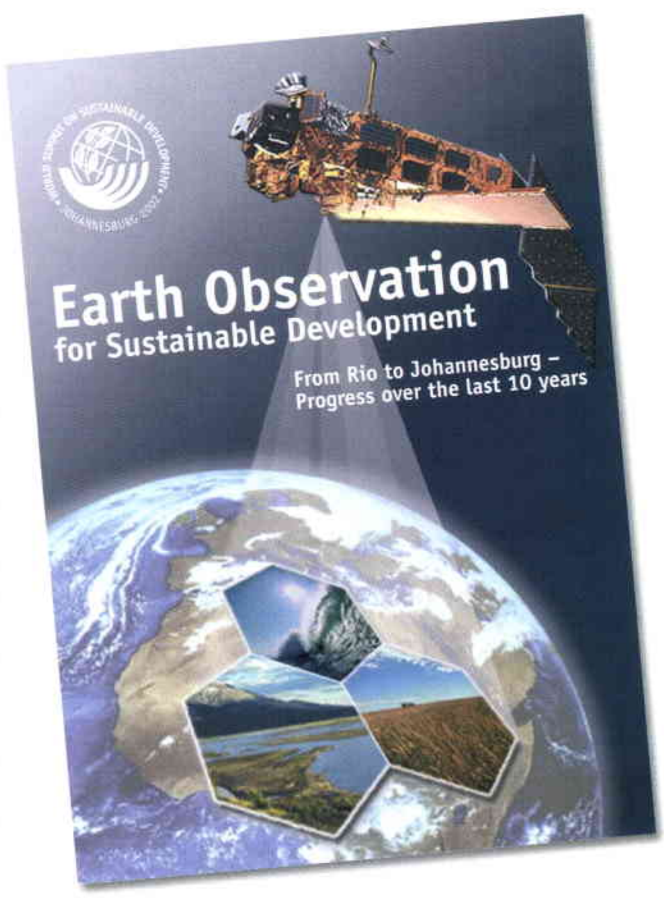
Comme nous l'avons vu plus haut, le problème de l'utilisation duale des systèmes spatiaux est clairement posé dans GMES, pour la prévision des catastrophes et la gestion des crises. Le programme franco-italien d'imagerie à haute résolution en cours d'élaboration, qui regroupe le projet français Pleiades et le projet italien Cosmo-Skymed, répond bien à ces besoins et s'inscrit parfaitement dans les objectifs de GMES. S'agissant d'un programme opérationnel, un tel système offrira une garantie de continuité des observations essentielle pour en faire un instrument permanent des sécurités civiles dans le monde. Il permettra en effet de gérer les aspects opérationnels des situations de catastrophes majeures, tels que les inondations et les tremblements de terre, de réaliser l'évaluation des dégâts et de planifier l'organisation des secours. Cette constellation apportera non seulement la haute résolution et la capacité 'tous temps' permise par les radars, mais également des possibilités de programmation rapide, indispensables en situation de crise.

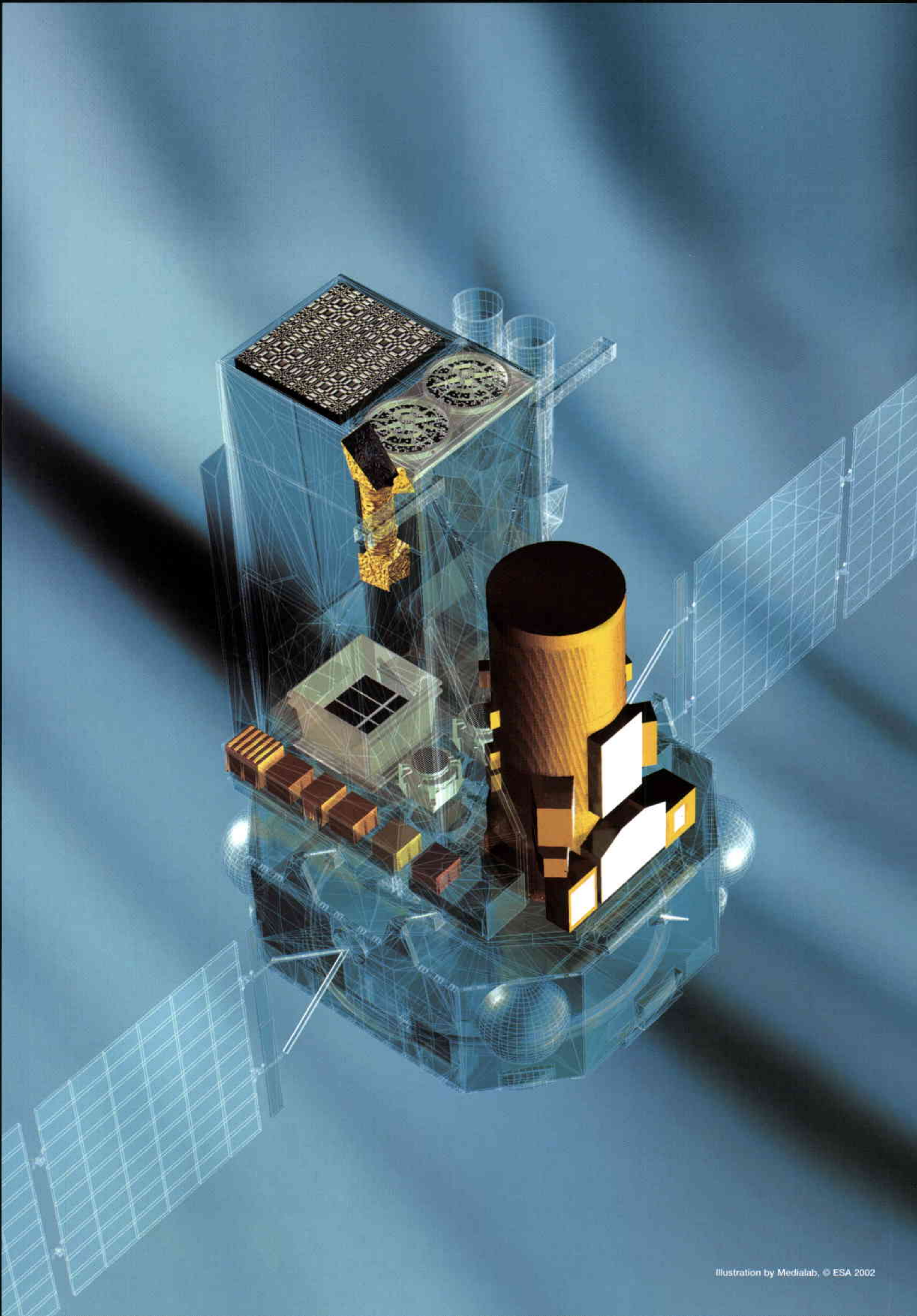
Les systèmes de télécommunications sont également appelés à jouer un rôle opérationnel important pour la prévention et la gestion des risques. La mise en orbite prochaine des satellites Artemis de l'ESA et Stentor du CNES permettra de démontrer comment les satellites de télécommunication peuvent contribuer à GMES dans l'acheminement rapide des données d'observation vers les centres de traitement et les utilisateurs ou encore dans le maintien des communications et le contrôle des opérations dans les situations de catastrophe naturelle. Envisat utilisera cette capacité pour fournir à ses utilisateurs, qu'ils soient scientifiques ou opérationnels, des données NRT (near-real-time) en moins de trois heures.

L'Europe et la gouvernance mondiale de l'environnement

A travers un programme comme GMES, l'Europe disposera de nombreux atouts dans le débat sur la mondialisation et le développement durable. Les différentes manifestations qui ont stigmatisé les récentes réunions du G8 et de l'OMC, de Seattle à Gênes, ou celles contre les transports de déchets nucléaires expriment clairement les préoccupations environnementales qui émergent de ce débat. Qu'on ne s'y méprenne pas, les 'Tutti Bianci' et autres manifestants du sommet de Gênes ne marchent pas contre la mondialisation. Ce qu'ils expriment est davantage un souci extrême de la planète et de son avenir. Et c'est bien naturel pour cette génération qui a grandi avec Internet, dont tous les symboles sont mondiaux et pour qui le village planétaire est bien davantage qu'un slogan politique ou un argument de librairie. Elle n'éprouve pas les difficultés de ses aînés à se situer dans ce monde où chacun peut poursuivre ses études sur plusieurs continents différents et où un voyage au bout du monde peut s'organiser en quelques heures grâce aux agences de voyage en ligne. Au contraire, pour cette génération, les questions de partage de souveraineté entre les états, l'Europe et les organisations internationales peuvent paraître dépassées, quand eux-mêmes réclament simplement davantage de régulation, d'équilibre et de justice dans la gouvernance de leur planète qu'il s'agisse du règlement de la dette des pays pauvres, de la régulation des flux de capitaux, de la réduction des inégalités entre le Nord et le Sud, de l'accès à l'information et à l'éducation ou encore de la protection de l'environnement et de la sécurité.

En prenant le leadership d'un programme GMES de surveillance globale de l'environnement et de la sécurité, l'Europe se posera également en interlocuteur de grandes puissances comme la Russie, la Chine et l'Inde. Celles-ci sont, en effet, particulièrement préoccupées par l'effet de serre et ses conséquences. D'abord parce que ces pays seront parmi les plus gros contributeurs aux émissions de gaz à effet de serre. Mais surtout parce qu'ils seront, d'après les simulations dont nous disposons aujourd'hui, les plus durement touchés, avec les pays en développement, par les conséquences du changement climatique. Les inondations, les sécheresses, les cyclones et les séismes que ces pays endurent sont chaque année plus catastrophiques. Ainsi, ces pays ont déjà fait connaître leur intérêt et leur volonté de participer à un tel effort mondial et, en particulier, au programme GMES. Le Sommet Mondial sur le Développement Durable qui se tiendra cette année à Johannesburg, dix ans après Rio, sera la prochaine grande étape dans l'élaboration de cette gouvernance environnementale de notre planète. La place qu'y tiendra l'Europe est à la fois un défi et une opportunité. C'est aussi un enjeu majeur pour l'avenir de la planète. GMES sera l'un de ses atouts.





Integral – Ready to Fly!

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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.

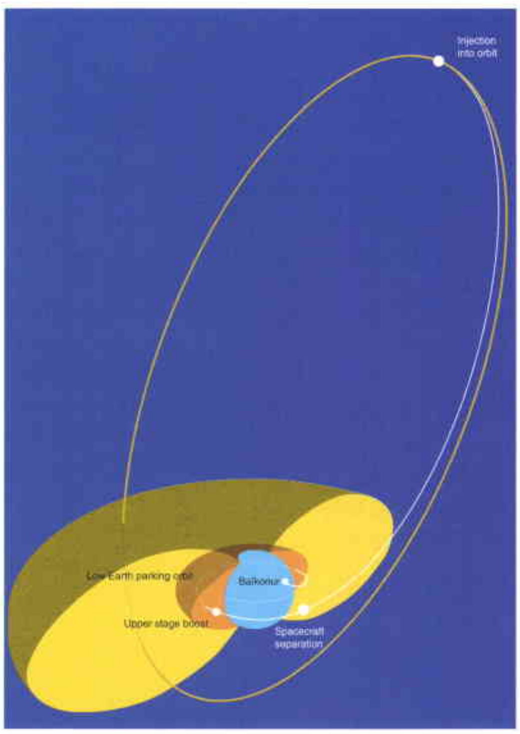


Figure 2a. Schematic of Integral's operating orbit and a cutaway view of the radiation belts in yellow

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,

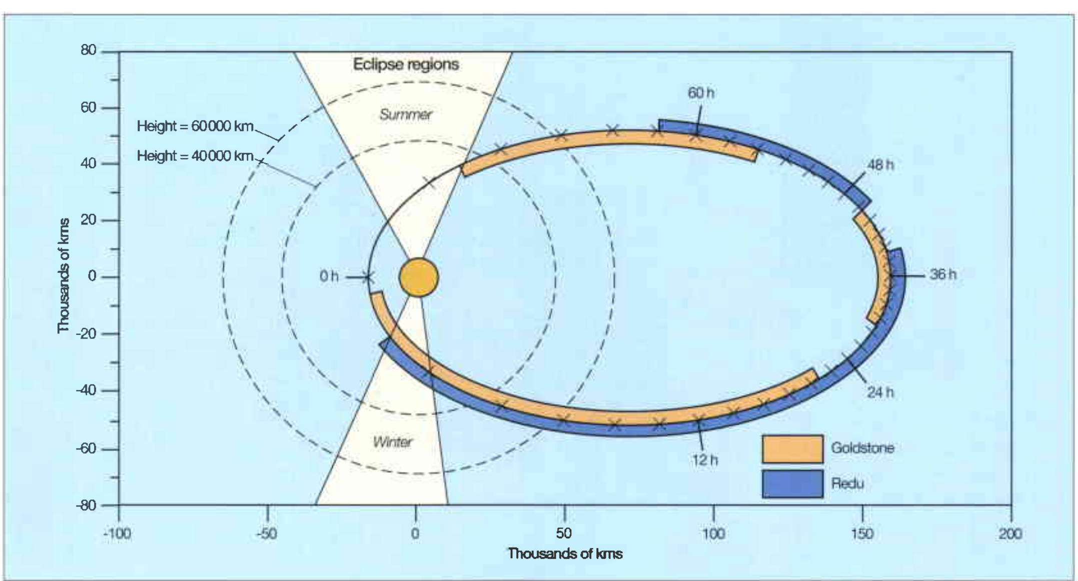


Figure 2b. Eclipse regions and telemetry coverage from the Redu (B) and Goldstone (USA) ground stations immediately after launch

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.

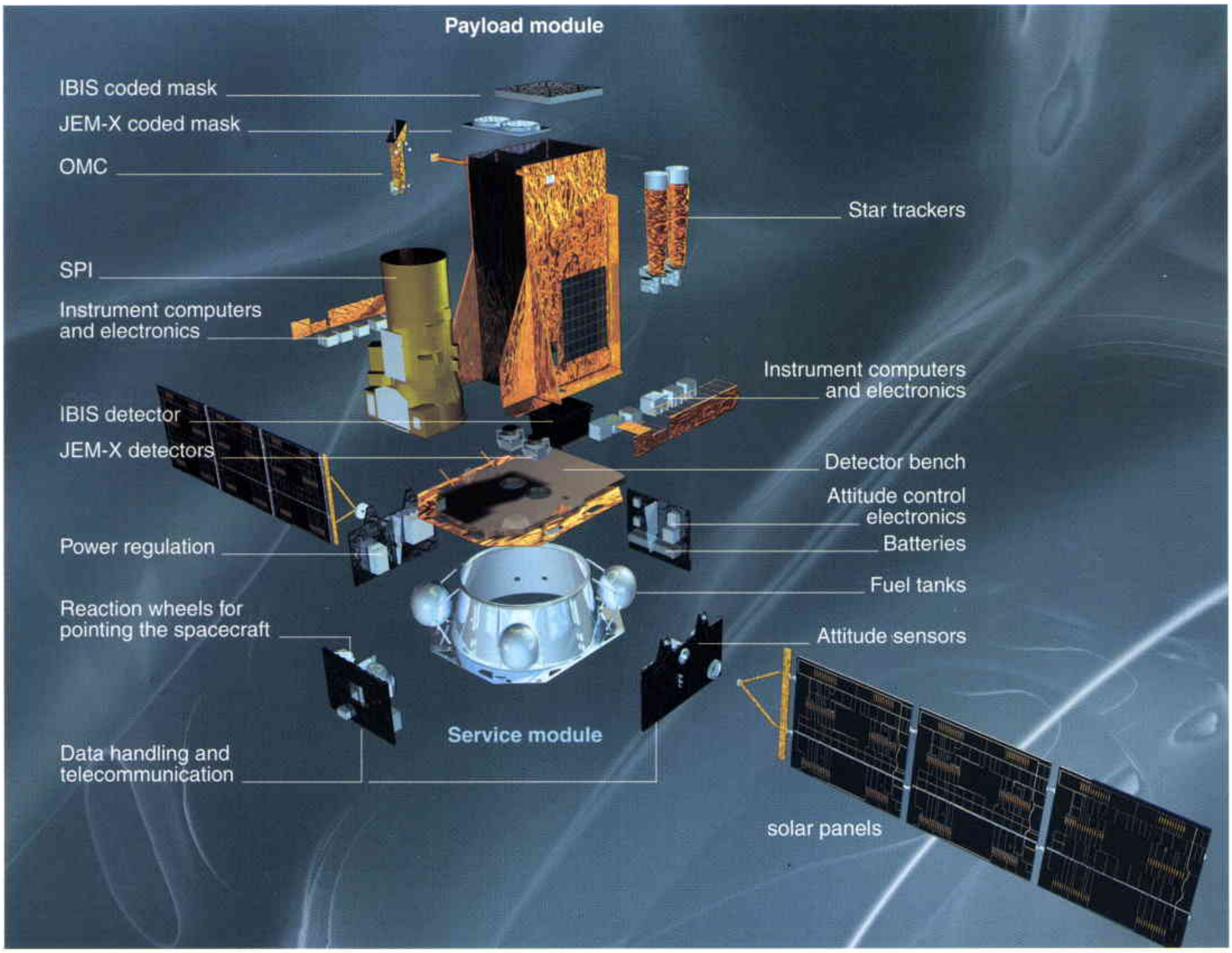
The Onboard Data Handling (OBDH) subsystem's main functions are to distribute commands, to sample/format telemetry data, and to provide data-processing services. The OBDH is built around the ESA standard OBDH bus and is fully compatible with the ESA Standards for Packet Telemetry and Packet Telecommands. 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

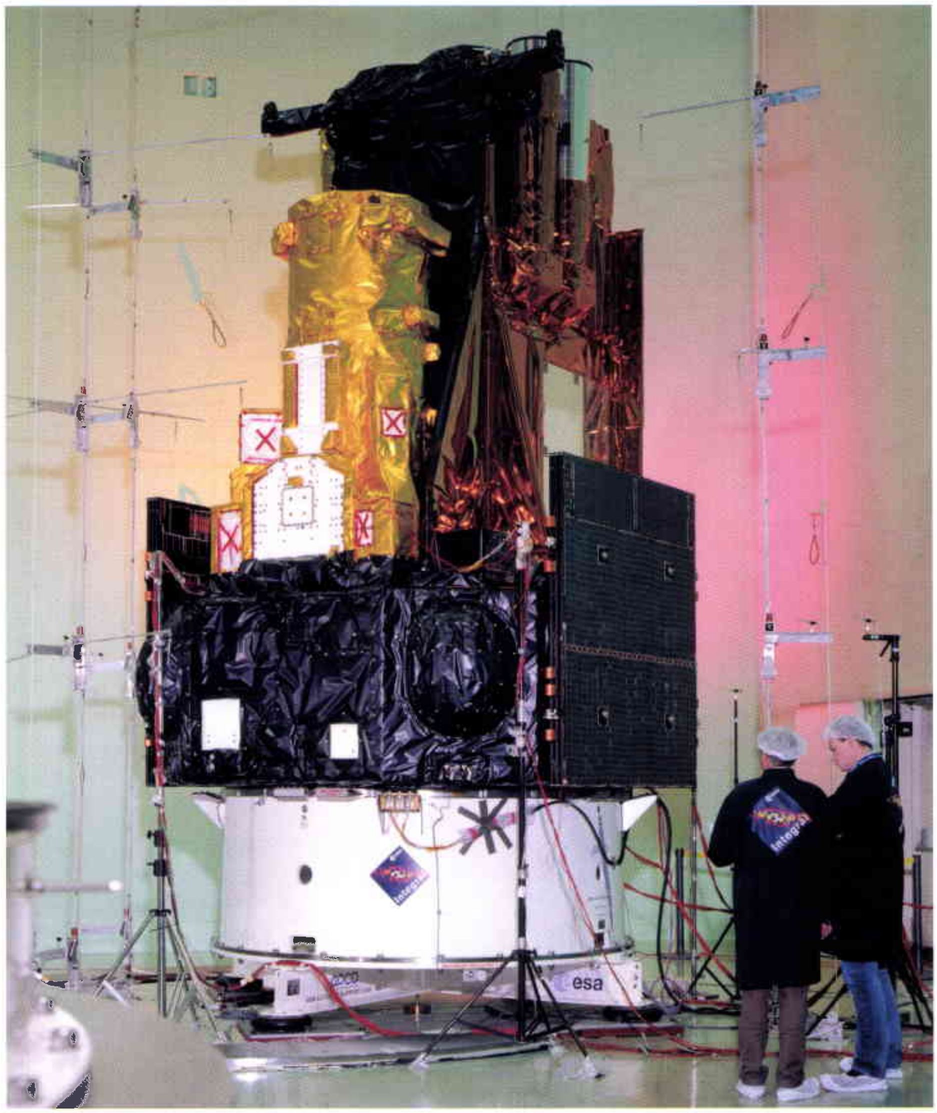


Figure 4. Integral in the Acoustic Test Facility at ESTEC

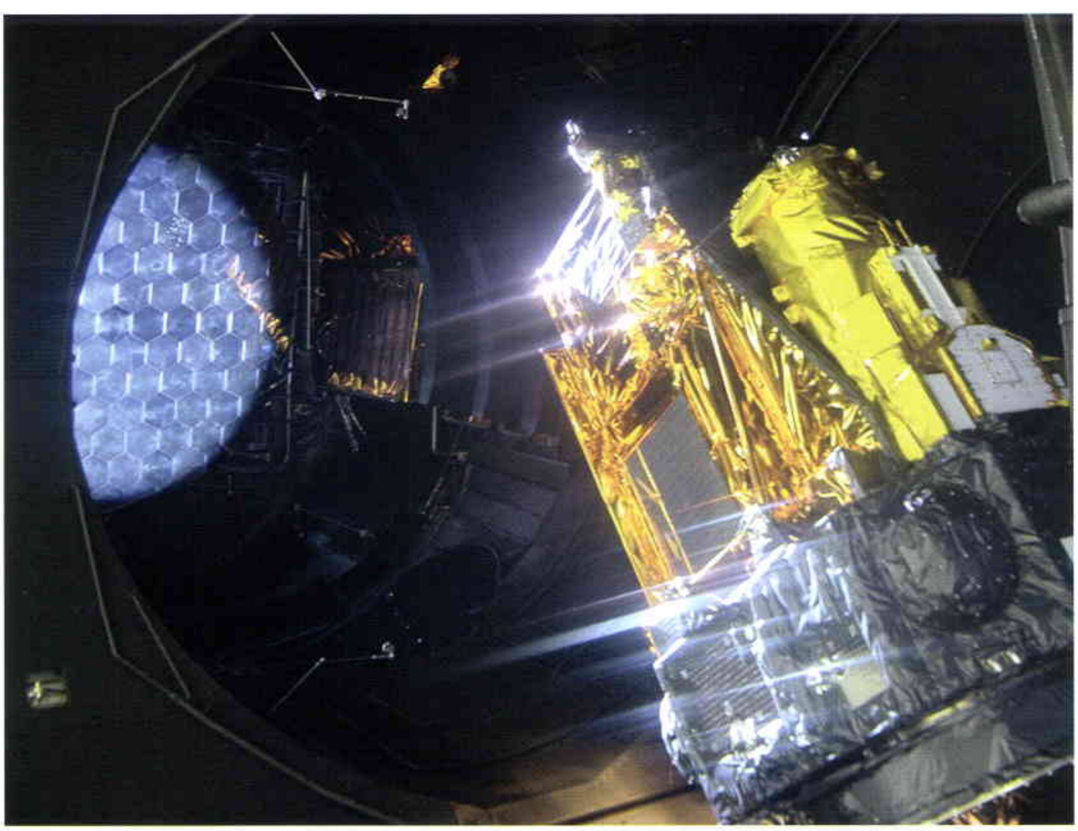


Figure 5. Integral in ESTEC's Large Space Simulator (LSS) for thermal-vacuum testing

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

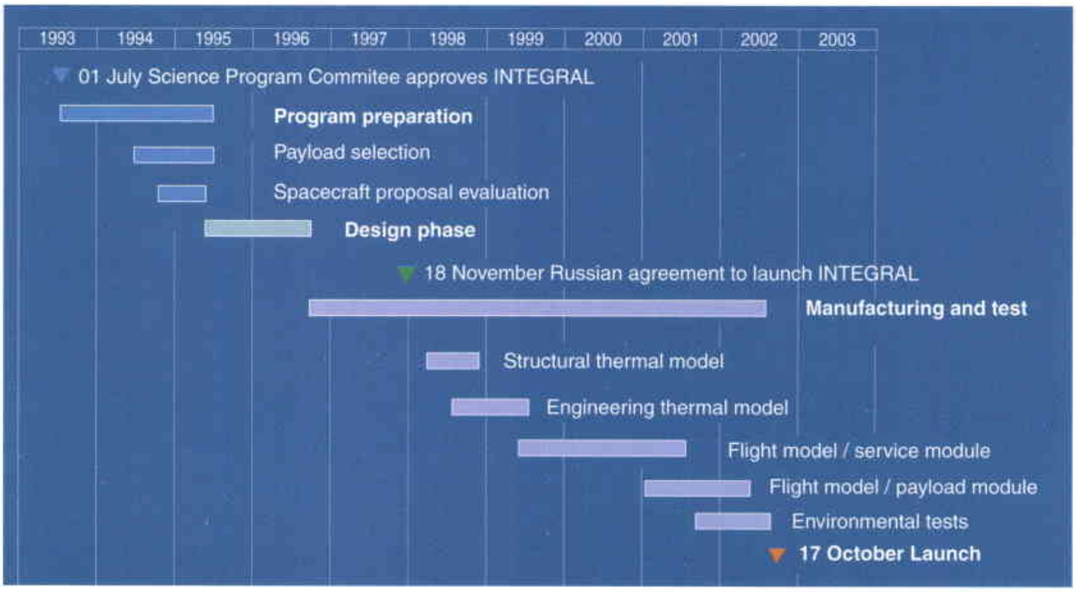


Figure 6. Integral project schedule

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.

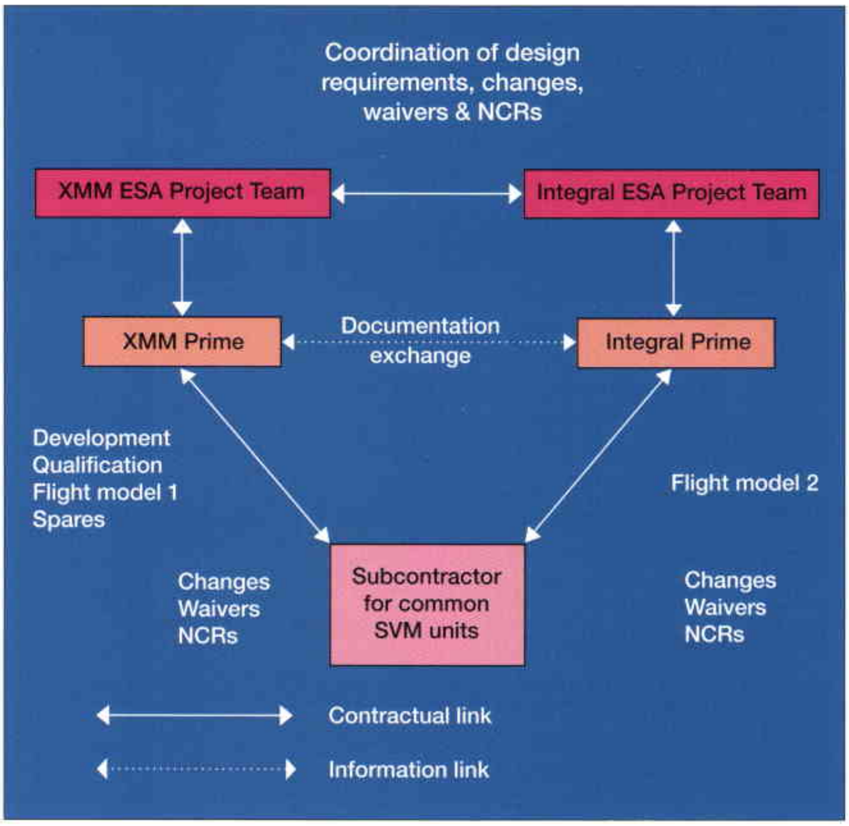


Figure 7. Implementation of the Integral/XMM commonality approach

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 Investigator 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.

The Integral Payload

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Introduction
Gamma-ray astronomy is more complicated than other branches of astronomy because at high energies matter is transparent, and therefore source detection and imaging cannot be accomplished with standard optical-like technologies. In addition, the weakness of the source fluxes calls for instruments with large detector areas, which tends to make them large and heavy.

Gamma-rays represent one of the most energetic forms of radiation in nature. They carry large quantities of energy radiated from some of the cataclysmic of all astronomical events, including exploding stars, colliding neutron stars, particles trapped in magnetic fields, and matter being swallowed by black holes. Integral's payload instruments – IBIS, OMC, JEM-X and SPI – will study these gamma-rays through detailed imaging and high-resolution spectroscopy, providing astronomers around the World with their clearest views yet of the most extreme environments in our Universe.

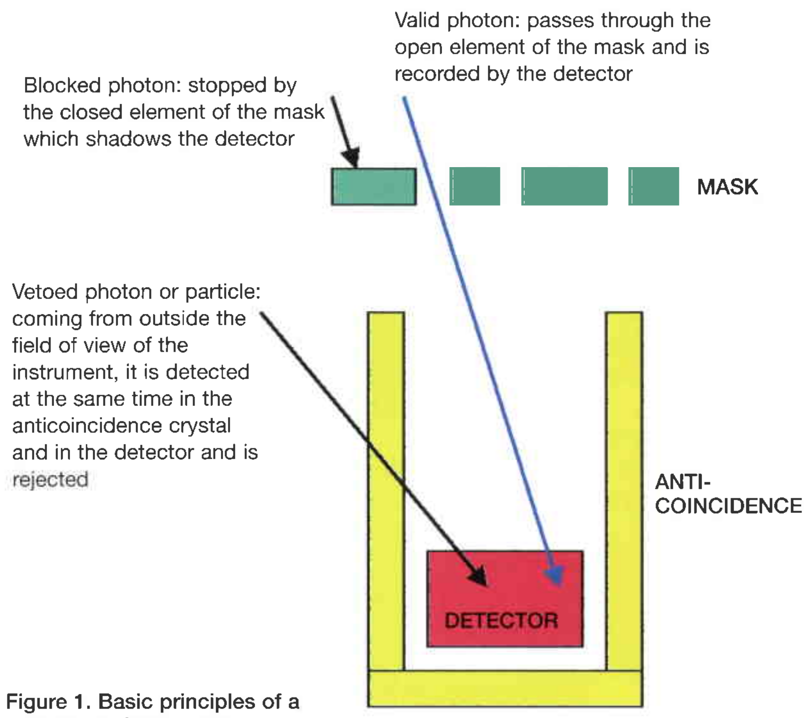


Figure 1. Basic principles of a gamma-ray instrument

The first problem to be solved is how to make an image of a source when the incoming light cannot be focussed, i.e. it passes through most materials without being deviated. The solution adopted for Integral is to use a method known as the 'coded-mask technique' (Fig. 1). The concept is simple, even if the associated mathematics is far from trivial. A coded mask can be seen as a chessboard where the black squares are made of very thick and heavy material with high atomic number, and the white squares are either empty or made of very light and thin material. The incoming gamma-ray radiation is stopped by the black elements, but is unaffected by the white elements. Any source will cast a shadow on the detector, placed a few metres below the mask. From the kind of shadow produced and knowing the geometric characteristics of the mask (the so-called 'code'), the position and shape of the source in the sky can be reconstructed on the ground. Of course, the presence of several sources in the sky, the effect of the external and internal backgrounds, and the fact that the geometry of the mask is much more complex than a simple chessboard, make the image reconstruction a complex mathematical exercise.

The second problem is how to image only what it is in the field of view of the instrument, and to exclude photons or high-energy particles reaching the detector from other directions. This could be achieved by surrounding the detector with a structure of material so thick and heavy that it is able to stop any undesired radiation. Unfortunately, this is not practical for two reasons: firstly, the structure will weigh several tons, and secondly too much material around the detector will create even more disturbance due to emissions of secondary radiation. The technique actually used is called 'active anti-coincidence' and the Anti-Coincidence System (ACS) is a key element of most gamma-ray instruments. The ACS consists of several blocks of thick crystal surrounding the detector, with the exception of the field of view. When the crystal is hit by a

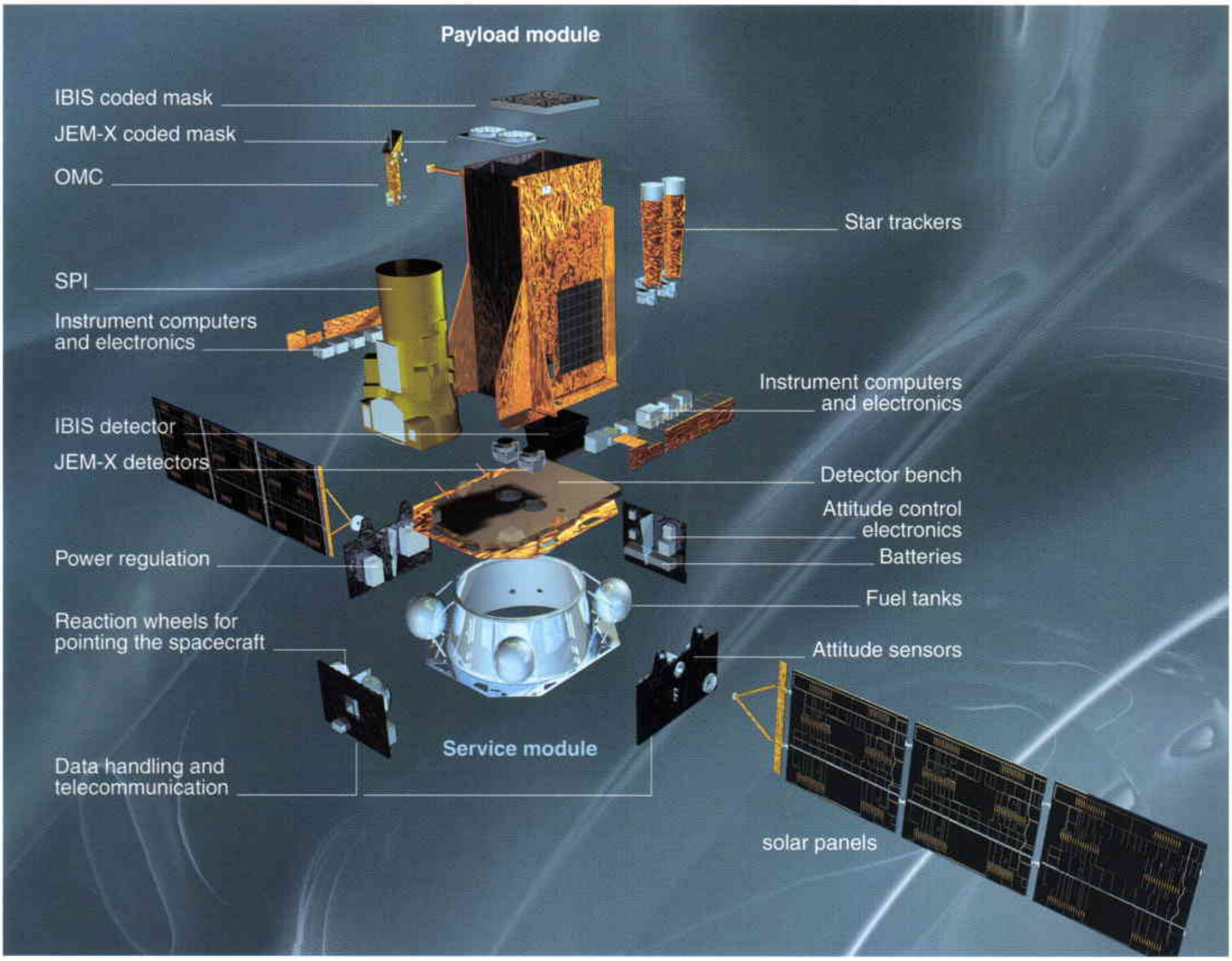


Figure 2. The four Integral instruments are integrated on the upper structure of the satellite, known as the Payload Module (PLM) (illustration Medialab)

particle or a photon, it generates a flash of light, which can be recorded in time. If the timing coincides with an event in the detector, the relevant particle or photon is considered as coming from outside the instrument's field of view and it is disregarded, or 'vetoed'.

The detector is the core element of the telescope where the interactions with the photons take place and the relevant signals are generated. Three interaction mechanisms are involved: the photoelectric effect, Compton scattering and pair production, depending on the energy of the incoming photon. The higher the energy that has to be measured, the greater must be the stopping power of the detector, and therefore its thickness. The quality of the image generated by the telescope, i.e. its spatial resolution, depends on the number of elements constituting each detector, which in Integral's case ranges from a few tens to several thousands of crystals. As the goal of the Integral mission is precise imaging coupled with fine spectroscopy, the instrument detectors will also provide high-resolution line spectroscopy.

Integral's instruments

The Integral payload consists of two main gamma-ray instruments, and two monitoring instruments operating in the X-ray and optical bands (Fig. 2). The two high-energy instruments are the SPI (SPectrometer on Integral), and the IBIS (Imager on-Board the Integral Satellite). The X-ray monitor is the JEM-X (Joint European Monitor for X-rays), and the optical instrument is the OMC (Optical Monitoring Camera). All four instruments have been designed with good scientific complementarity in mind in terms of energy range, energy resolution and imaging capability. Each of the two main instruments has imaging and energy-resolution capabilities, but whilst the IBIS is best for imaging, the SPI is optimised for spectroscopy. The two monitors will provide complementary, but still fundamental, observations of the high-energy sources at X-ray and optical wavelengths.

Also forming part of the payload is a small radiation monitor, which will continuously measure the charged-particle environment of the spacecraft, particularly the electrons and protons. This will provide essential information

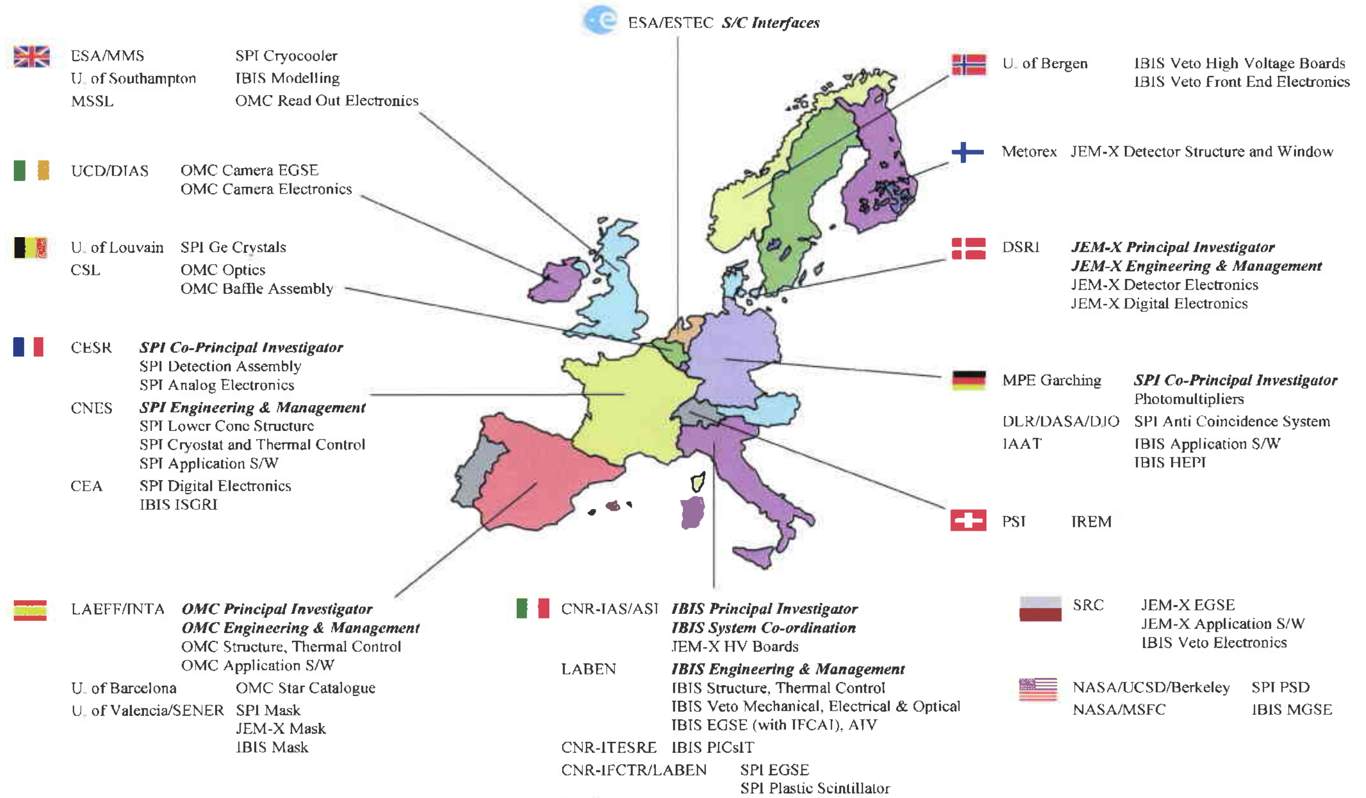


Figure 3. The Integral instrument consortia

Table 1. Summary of the Integral payload's main scientific performances

Parameter	SPI	IBIS	JEM-X	OMC
Energy Range	20 keV – 8 MeV	15 keV – 10 MeV	3 keV – 35 keV	V-filter (at 550 nm)
Detector Area	500 cm^2	2700 cm^2	1000 cm^2 (two units)	1.33 x 1.33 cm^2 1024 x 1024 pixels 50 mm aperture diameter
Energy Resolution	2.4 keV @ 1.33 MeV	8% @ 100 keV 9% @ 1 MeV	16% E > 6 keV	12 bits, 4095 digital levels
Fully Coded Field of View	16°	9° x 9°	4.8°	5° x 5°
Partially Coded Field of View	35°	29° x 29° (zero response)	13.2° (zero response)	
Angular Resolution	2.8° (FWHM)	12 arcmin (FWHM)	3 arcmin	17.6 arcsec x 17.6 arcsec
Point Source Location	30 arcmin	30 arcsec (ISGRI)	30 arcsec	
Continuum Sensitivity 3 σ in 10^6 sec	3 x 10^{-7} ph cm^{-2} s-1 keV^{-1} @ 1MeV, δE=1 MeV	5 x 10^{-7} ph cm^{-2} s^{-1} keV^{-1} @ 100 keV, δE=E/2 1.6 x 10^{-7} ph cm^{-2} s^{-1} keV^{-1} @ 1 MeV, δE=E/2	1.3 x 10^{-5} ph cm^{-2} s-1 keV^{-1} @ 6 keV 8 x 10^{-6} ph cm^{-2} s^{-1} keV^{-1} @ 30 keV	
Line Sensitivity 3 σ in 10^6 sec	2 x 10^{-5} ph cm^{-2} s^{-1} @ 1MeV	1.1 x 10^{-5} ph cm^{-2} s^{-1} @ 100 keV 5 x 10^{-5} ph cm^{-2} s^{-1} @ 1 MeV	1.7 x 10^{-5} ph cm^{-2} s^{-1} @ 6 keV 5 x 10^{-5} ph cm^{-2} s^{-1} @ 30 keV	
Timing Accuracy 3 σ	160 μs	120 μs – 30 min	122 μs	2 ms (frame transfer time) 3 s (time resolution)
Limiting Magnitude				17.6 (10 x 100 sec, 3 σ) 18.2 (50 x 100 sec, 3 σ)
Sensitivity to Variations				m_V < 0.1, for m_V < 16 (15 x 100 sec, 3 σ)

to the payload in cases where high particle backgrounds (radiation belts, solar flares) are being encountered, allowing instrument high voltages to be switched off and on as appropriate, and will also provide background information for sensitivity estimates.

The four scientific instruments have been provided by separate scientific consortia, each led by a Principal Investigator, or PI (Fig. 3). They are nationally funded, with ESA contributing the Data Processing Electronics (the dedicated onboard computers), the cryo-cooler, and high-reliability electronic components. The pre-processing and distribution of the scientific data to the science community will be the responsibility of the Integral Science Data Centre (ISDC), which is also nationally funded via a PI-led consortium. A summary of the Integral payload's main scientific performances and spacecraft resource allocations is given in Tables 1 and 2.

SPI (Spectrometer on Integral)
PIs: J.P. Roques (formerly G. Vedrenne) (CESR, Toulouse) and V. Schönfelder (MPE, Garching)

The SPI is a spaceborne spectrometer designed to perform high-resolution gamma-ray spectroscopy (Fig. 4). The instrument will explore the most energetic phenomena that occur in the Universe, such as neutron stars, black holes, supernovae and the most fundamental problems in physics and astrophysics, such as nuclear de-excitation, positron annihilation, and synchrotron emission. To meet its scientific objectives, the instrument has to satisfy very challenging measurement requirements. It has thus been designed to provide good angular resolution and an excellent energy resolution in the range 20 keV – 8 MeV, with imaging and accurate positioning of point sources (~2.8°) or extended celestial gamma-ray emissions. The SPI's detection, shielding and imaging capabilities for high-energy photons rely on three main features: a 19-detector focal plane, an active shielding telescope and a passive coded mask.

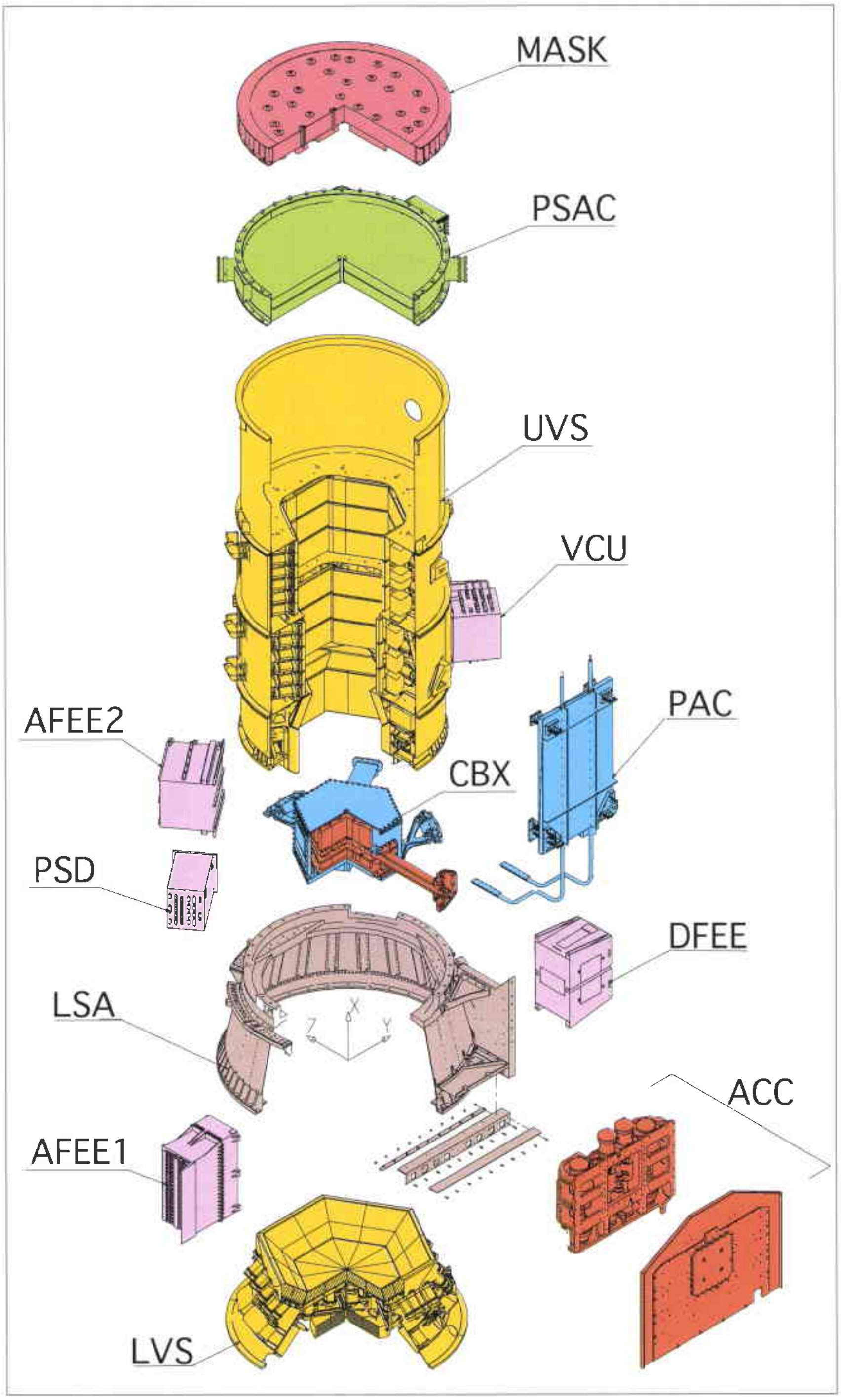


Figure 4. Exploded view of the Spectrometer (SPI), with the core of the instrument, the detector element, housed in a cryostat (courtesy of CNES)

Table 2. Summary of spacecraft resources allocated to the Integral payloads (including DPE)

Instrument	**SPI**	**IBIS**	**JEM-X**	**OMC**	**Total**	**% of spacecraft resources**
Mass	1273 kg	731 kg	76 kg	23 kg	2103	53 %
Peak power in sunlight	384 W	234 W	68 W	26 W	712 W	45 %
Average power in eclipse	159 W	8 W	8 W	17 W	192 W	26 %
Data rate	Up to 20 kbps	Up to 60 kbps	Up to 8 kbps	Up to 2 kbps	Up to 86 kbps	95 %

The mask, located on the top of the SPI, holds a coded motif of tungsten blocks (63 opaque elements and 64 transparent elements). The tungsten stops gamma-rays in the energy range 20 keV – 8 MeV with an effective blocking power greater than 95% at 1 MeV. Similarly, the 'holes' have a 60% transparency at 20 keV and 80% at 50 keV. The Plastic Scintillator Anti-Coincidence (PSAC) sub-assembly located below the mask reduces the background due to the mask's 511 keV secondary radiation emission. It is composed of a plastic scintillator enclosed in a light-tight box with photo-multiplier tubes that convert the light flashes into electrical pulses. The signals are processed by the PSAC electronics, which send a synchronous veto signal associated with the detected events to the active shielding control electronics (Veto Control Unit).

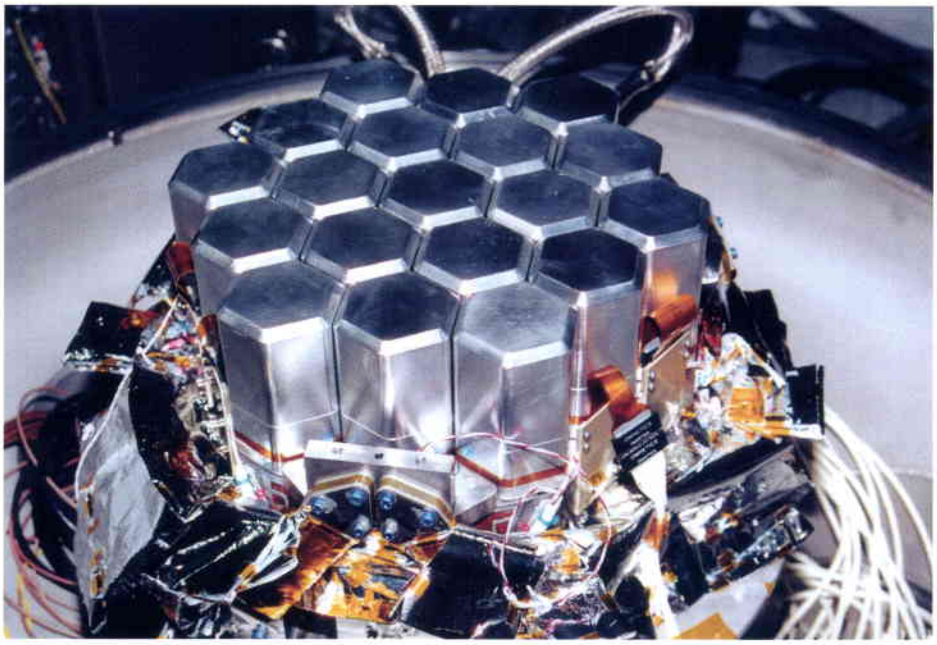


Figure 5. The SPI detectors, consisting of 19 encapsulated germanium crystals mounted on a cold plate, which is nominally maintained at 90 K by four Stirling mechanical coolers (courtesy of CESR)

The detection plane is made of 19 encapsulated, hexagonal, high-purity germanium detectors mounted on a 'cold plate' cooled to 90 K (Fig. 5). The detection plane is itself placed in a thermally insulated 'cold box' (CBX), whose temperature is maintained at approximately 210 K by passive cooling. Wherever possible, the box's structure has been manufactured from beryllium (limiting the generation of secondary radiation background noise in the detectors). The cooling of the detectors is achieved via the Cold Bus Bar linking the cold plate to the Active Cooling (ACC) sub-assembly composed of two pairs of cryocoolers (four compressors and four displacers). The cryocoolers are fixed onto a radiator, itself mounted on the structure (LSA) supporting the instrument active shielding and other

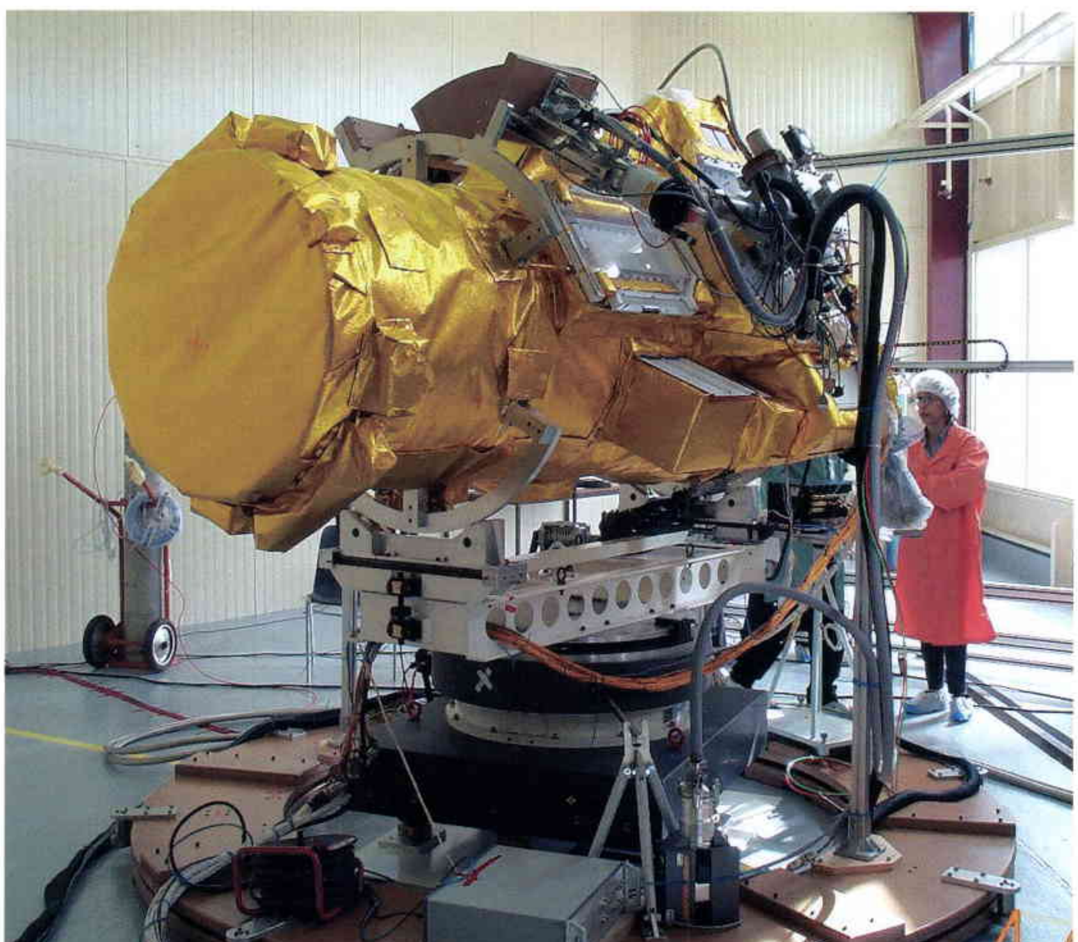


Figure 6. The SPI during calibration activities at the Centre d'Etudes Atomiques in Bruyères le Chatel (F) (courtesy of CESR/CEA/CNES)

electronics. A radiator (PAC) mounted on the structure of the active shielding performs passive cooling of the cold box via two ammonia heat pipes. Each pair of cryocoolers is controlled by a separate Cooler Drive Electronics (CDE) unit located on the Payload Module platform near the SPI (Fig. 6).

The bias voltage of each germanium detector is programmable up to 5000 V. Dedicated high-voltage filters (located on the cold plate) and charge-sensitive amplifiers (operating at 200 K) amplify the signal produced by each detector. A pulse-shape amplifier and pulse-height analyser located in the Analogue Front-End Electronics (AFEE 1) process this signal further. The low-voltage supplies for the 19 amplification chains as well as the germanium-detector high-voltage power supplies are located in AFEE 2.

The Anti-Coincidence System is made up of scintillator crystals (bismuth germanate oxide), photomultipliers tubes (182 PMTs) with the associated electronics (91 FEE) and a shielding Veto Control Unit (VCU). The key function of the active anti-coincidence sub-assembly is to protect the detection plane against the background (photons and charged particles) from sources located outside the field of view. To that end, the scintillator crystals encircle 60% of the telescope's height, as well as enclosing the back of the detection plane. The crystals convert all incoming events into photons of approximately 480 nm wavelength. The light flashes produced are converted by the photomultiplier tubes into electrical pulses. These, in turn, are sorted, normalised and summed by the ACS electronics. The VCU is responsible for the proper functioning and health of the ACS, performing the overall monitoring and control.

The task of the Pulse Shape Discriminator (PSD) is to actively reduce the instrumental background in the 200 keV – 2 MeV energy range by pulse-shape discrimination. It digitises the current pulses from single detector events that correspond to photon energies in the above-specified range. The observed current pulses are then compared on-board with a library of single-site current-pulse templates stored in the sub-assembly, to distinguish single-site from multiple-site interactions within the germanium detectors. By rejecting single-site and retaining only multiple-site events, active background reduction is achieved, leading to a sensitivity improvement of about a factor two within the PSD energy range.

The Digital Front-End Electronics (DFEE) performs the real-time acquisition, assembly, time-stamping and intermediate storage of the various events detected by the Spectrometer. It first compensates for the differential delays that may occur in the different electronics chains. After this 'time alignment', the AFEE and PSD events observed in one or more detectors are recorded, with their time of occurrence, relative time, AFEE energy, and PSD identifier (single- or multiple-site interaction). Whenever the ACS activates the veto signal, events that occurred in that time period are marked as vetoed and handled separately. The DFEE delivers the annotated lists of AFEE or PSD non-vetoed events to the Digital Processing Electronics (DPE) for inclusion in the telemetry packets.

The DPE, located on the Payload Module close to the instrument, acts as the functional interface between the instrument and the Service Module. It performs the instrument commanding (operating modes) and monitoring (house-keeping management), as well as the scientific data management (i.e. building the spectra and transmitting the data packets to the spacecraft's data-handling system for transmission to ground).

IBIS (Imager on-Board the Integral Satellite)
PI: P. Ubertini (CNR-IAS, Rome)
Co-PIs: F. Lebrun (CEA, Saclay) & G. Di Cocco (CNR-ITESRE, Bologna)

The IBIS will provide high-resolution images of celestial objects of all classes, ranging from the most compact galactic systems to extra-galactic objects (Fig. 7). Better than any previous imaging instrument operating in the gamma-ray range between 15 keV and 10 MeV, IBIS will achieve an angular resolution of 12 arcmin and a spectroscopic resolution of 8–9 % over the range 0.1–1 MeV.

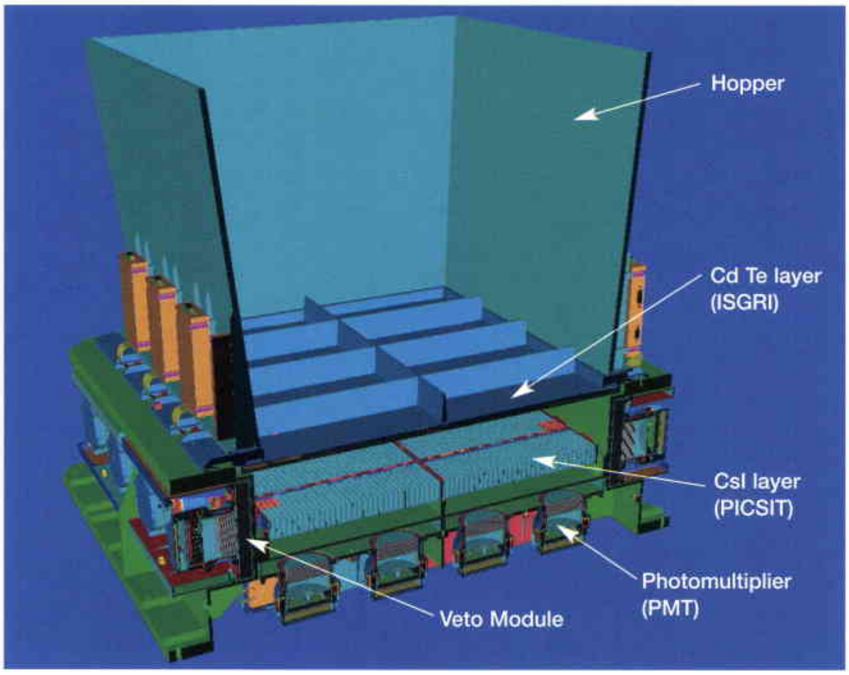


Figure 7. Cut-away view of the IBIS detector unit. The two crystal layers, the ISGRI (low-energy detection) and the PICSIT (high-energy detection), are surrounded by the veto modules of the anticoincidence system. The collimator (hopper) is made of CFRP covered by a layer of tungsten (courtesy of Laben)

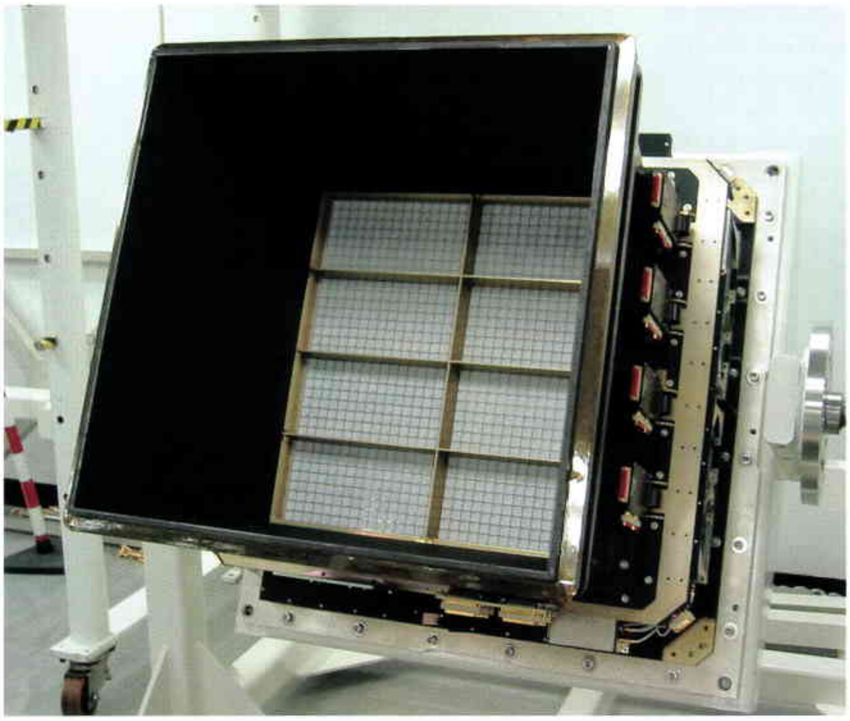
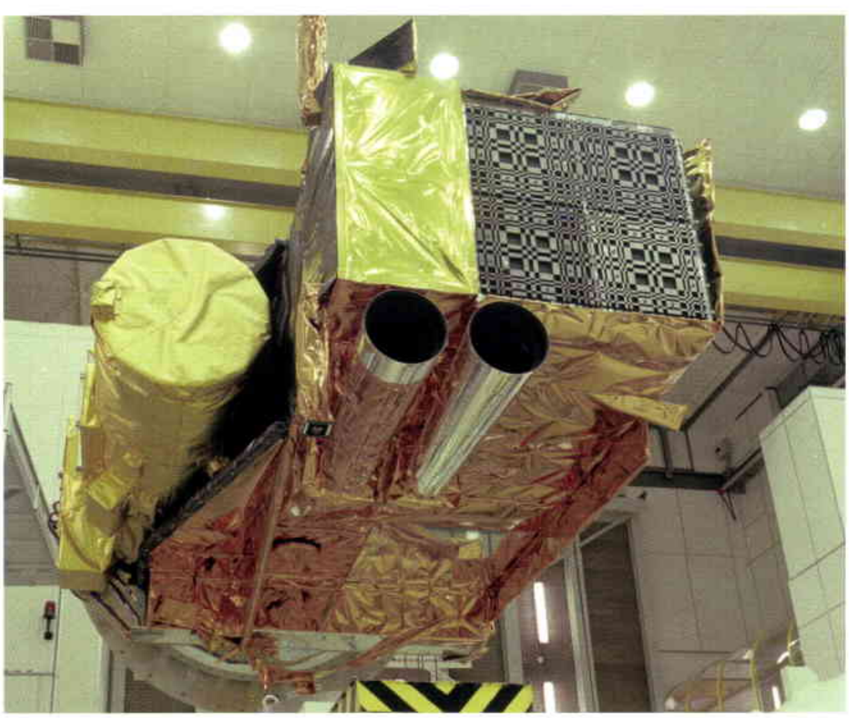


Figure 8. The IBIS detector unit. The eight modules of the upper detector layer can be seen at the bottom of the collimator. Each module is made up of 2048 sensing elements.
(courtesy of CNR-IAS/CEA and Laben)

Figure 9. The IBIS mask on top of the Integral Payload Module. The two JEM-X masks are covered by the thermal blanket. The baffle of the OMC is visible in the upper part of the picture, and the two star trackers in the lower part. On the left is the SPI

The imaging capability of the instrument is provided by casting a 'shadowgram' of a coded-mask aperture onto a two-layer position-sensitive detector (Fig. 8). The energy of the incoming gamma-ray photon, transferred to charged particles, is dissipated and measured with two parallel pixellised detector planes surrounded by an active anti-coincidence scintillation system. A total of 16 384 independent semiconductor crystals, made of cadmium telluride, constitute the upper layer of the detection unit, designed to cover the lower gamma-ray energy range from 15 keV to 0.5 MeV. High-energy photons are detected by the lower layer, made with 4096 caesium-iodide crystal scintillators. Time-coincident events in both planes resulting from Compton scattering are also analysed.



In order to reject background events as energetic particles, the sides of both planes as well as the back face are shielded by an active anti-coincidence system made of bismute germanate oxide (BGO) crystal scintillator blocks coupled with photomultipliers. A truncated carbon-fibre pyramid covered with a thin tungsten layer is placed on top of the detector as a collimating system to reduce the low-energy X-ray background. An on-board Calibration Unit (CU), consisting of a 22Na radioactive source in combination with a scintillator-based coincidence strobe generator, is included within the instrument as a known reference for in-flight calibration.

The coded mask is obtained from a pattern of 95 x 95 elements, covering a total area of 1064 x1064 mm^2. Half of the elements are made of 16 mm-thick tungsten, offering 70% opacity at 1.5 MeV; the remaining elements are open and consequently transparent to photons (Fig. 9).

The upper detection layer, the Integral Soft Gamma-Ray Imager (ISGRI), is made of eight identical, modularly organised detection units, providing a total sensitive area of 2621 cm^2. Each module contains 2048 independently operated CdTe detectors, 4 x 4 x 2 mm^3 in size. Due to the high number of pixels, specially developed Application-Specific Integrated Circuits (ASICs) convert the electrical charges into proportional voltage signals. Each ASIC is designed to support four pixels, and so 4096 ASICs have been manufactured for the IBIS flight model. Final processing of the analogue parameters is done by eight electronics units accommodated in two ISGRI Electronics Boxes (IEB 1 and 2).

The upper energy range of 200 keV – 10 MeV is covered by the Pixellated Imager Caesium-Iodide Telescope (PICsIT), which is located 90 mm below ISGRI. Like the ISGRI, the layer is modularly organised with eight rectangular detector units, each consisting of 512 tallium-doped caesium-iodide crystal scintillator bars of 8.35 x 8.35 mm^2 with a thickness of 30 mm. The bars are optically coupled and readout by custom-made low-leakage silicon photodiodes. 32 ASICs inside each module, containing pre-amplification, pulse shaping, amplification, signal discrimination, peak detection, and analogue storage, analyse the signals from the photo-diodes. Two separate PICsIT Electronics Boxes (PEB 1 and 2) process the detector signals and convert them into digital event-position and photon-energy information.

16 Veto Detector Modules (VDMs), each made of BGO scintillator crystal and analysed by two photomultipliers, function as anti-coincidence detectors for ISGRI and PICsIT events to reduce the detector background. Eight BGO modules are located below the two detector layers, and eight are placed around them. The signals from the photo-multipliers are routed to the Veto Electronics Box (VEB), in which the analogue signals are discriminated by programmable thresholds to generate binary veto signals. The VEB also controls the onboard Calibration Unit. The veto event signals are used directly by the ISGRI and PICsIT in order to reject coincident events.

During times of high photon fluxes, the IBIS may generate more events than can be transferred to ground with the allocated telemetry rate. A special pre-processing unit has therefore been built to enhance the spacecraft DPE's capabilities. It will accumulate data into onboard histograms, reconstruct multiple or Compton events, and calculate energy amplitude corrections using dedicated calibration tables.

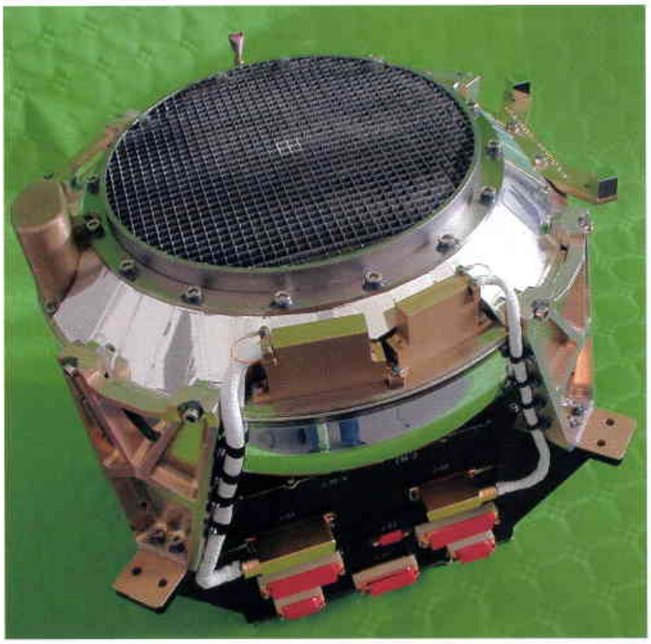


Figure 10. The JEM-X detector assembly. The upper element is the detector vessel, whilst the lower, black element is the Digital Front-End Electronics (DFEE). The square pattern of the collimator can be seen on the top of the detector vessel (courtesy of DSRI)

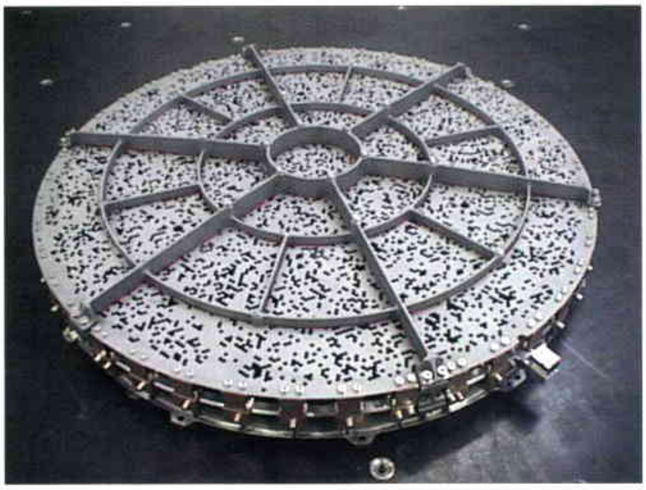


Figure 11. The JEM-X mask is made from a thin tungsten plate. The coded pattern is provided by a regular combination of small hexagonal holes. Supporting ribs are provided to carry the launch loads (courtesy of Univ. of Valencia/Sener)

JEM-X (Joint European X-Ray Monitor)
PI: N. Lund (DSRI, Copenhagen)

In order to have a comprehensive understanding of physical phenomena in the celestial sources observed by the SPI and IBIS, it is important to extend the energy range of the observations to the lower X-ray energy band. Therefore an X-ray monitor was needed in Integral's payload complement. JEM-X will provide images with an angular resolution as low as 3 arcsec in the 3 – 35 keV energy band (Fig. 10).

The instrument consists of two identical high-pressure micro-strip gas chambers, which view the sky through two identical coded masks (Fig. 11). For each of the two JEM-Xs, the X-ray photons entering the instrument's field of view pass through the holes in the coded mask, which is located about 3.4 m above the detector entrance window. Inside the detector, which is filled with a mixture of 90% xenon and 10% methane, the photons are absorbed by the xenon gas. This photon absorption process is mainly photoelectric and the emitted electrons ionise the other atoms, thereby generating an ionisation cloud. The cloud is amplified whilst drifting towards the detection plane, thanks to an electric field applied between the detector entrance window and the detection plane itself. The avalanche of ionisation is eventually detected by the micro-strip plate, which constitutes the detector focal plane (Fig. 12). The resulting electrical signal is proportional to the energy of the incoming photon. The position is determined by knowing on which anode/cathode group the charge is collected.

The imaging principle is the same as for the two other main instruments and is based on the coded-mask technique. The main hardware elements of the JEM-X are therefore the mask, the detector (with its key constituents the collimator, the pressure vessel with entrance window, and the micro-strip plate), the Digital Front-End Electronics for signal processing, and the dedicated onboard computer (DPE).

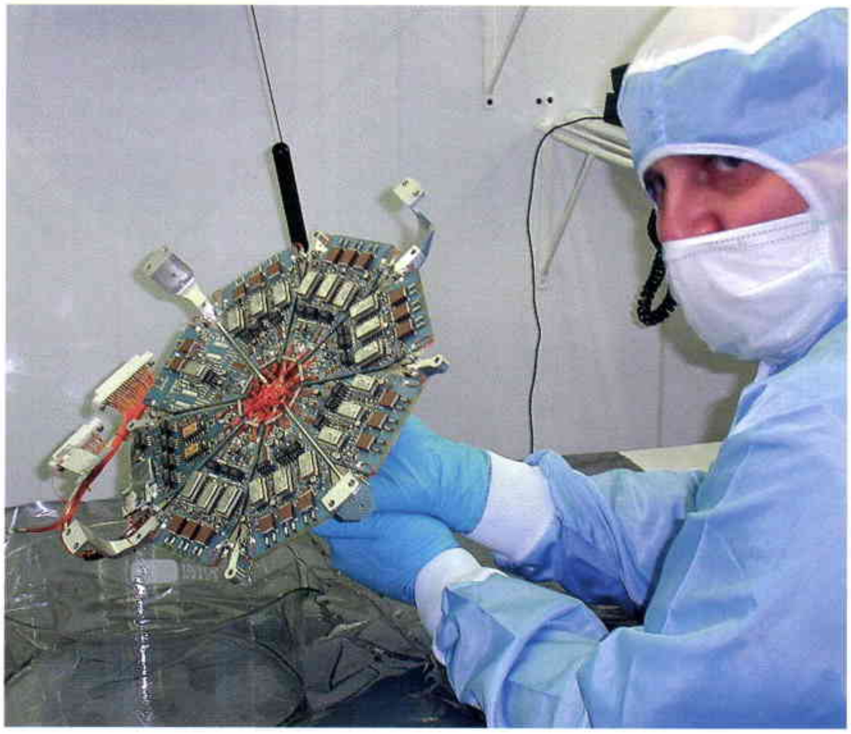


Figure 12. The micro-strip plate and its associated electronics are the core elements of the JEM-X detector. Due to their extreme sensitivity to contamination, all assembly operations have been carried out in an extra-clean environment (courtesy of DSRI)

The coded mask is a plate of tungsten 0.5 mm thick and with a diameter of about 0.5 m. Due to its thinness, it behaves like a membrane, and the titanium supporting structure has a pre-tensioning system to help keep the natural frequency above the forcing frequencies that will be experienced during launch. The mask elements are hexagonal and 3.3 mm in size, and the holes are produced by electrical erosion. The collimator, located on top of the detector vessel, reduces the background and limits the instrument's field of view to about 6 deg, which is also driven by the detector-mask combination. Its cells are square in shape and it is made of molybdenum. Four small radio-active sources mounted on the collimator will serve as references for the in-flight calibration of the instrument. The collimator also has a structural function, which is to protect the very thin entrance window against the internal detector pressure and the launch loads.

The entrance window must be as thin as possible and is made from a metal with a low atomic number to allow good transmission of the low-energy (3 keV) X-rays. A 0.25 mm-thick beryllium foil has been selected. The detector micro-strip plate and its basic conditioning electronics are contained in a stainless-steel vessel. The gas inside the vessel has a nominal pressure of about 1.4 bar. The micro-strip plate is the sensing element of the detector and is the equivalent of the wires in a classical multiwire proportional chamber. It is made up of a pattern of alternating cathode and anode strips with a pitch of 1 mm, built on a glass-plate substrate. This pattern gives one coordinate in the detection plane, and the orthogonal coordinate is given by a set of pickup electrodes on the rear surface of the glass plate. The micro-strip plate is surrounded by a veto electrode, which is used to suppress events caused by charged particles entering the detector from the side.

The instrument electronics are physically distributed in three locations. The detector vessel hosts the first level, whose purpose is analogue signal processing and high-voltage distribution to the micro-strip sensors. The second level is a dedicated box called the Digital Front-End Electronics, which performs the digital elaboration of the signals. It also generates, controls and distributes the high voltage and the secondary voltages to the instrument. The last element is the Data-Processing Electronics, which is also a separate unit provided and controlled by the satellite. Its functions are data reception from the front end, data compression, and the management of all telemetry and telecommand interfaces with the satellite.

Three JEM-X flight units have been manufactured, two flight units and one flight spare. The two JEM-X units on the spacecraft will be operated independently and simultaneously, thereby making the instrument fully redundant with respect to any possible failure.

OMC (Optical Monitoring Camera)
PI: M. Mas-Hesse (formerly A. Gimenez) (LAEFF/INTA, Madrid)

The Integral model payload was designed to study simultaneously high-energy sources in a wide field of view over many decades in energy, and thus to make a major contribution to short-time-scale high-energy astrophysics. The OMC (Fig. 13) observes the optical emission from the prime targets of the two gamma-ray instruments with the support of the X-ray monitor. This capability provides information on the nature and the physics of the sources over a broad wavelength range. Multi-band observations are particularly important in high-energy astrophysics, where variability is typically rapid, unpredictable and of large amplitude. The main scientific objectives with OMC are therefore to:
- monitor the optical emission of all high-energy targets within its field of view, simultaneously with the high-energy instruments
- provide simultaneous and calibrated standard V-band photometry of the high-energy sources, to allow comparison of their high-energy behaviour with previous or future ground-based optical measurements
- analyse and locate the optical counterparts of high-energy transients detected by the other instruments, especially gamma-ray transients

- monitor any other optically variable source within the OMC field of view which may require long periods of continuous observations for their physical understanding.

The OMC is also designed to provide data for the estimation on the ground of the precise pointing of the observatory with an accuracy of a few arcseconds. This information allows the Imager, Spectrometer and X-ray monitor images to be reconstructed on the ground with maximum angular resolution.

The OMC consists of a charge-coupled-device camera unit (Fig. 14) connected to a single electronics unit. The core of the unit is a large-format CCD (2048 x 1024 pixels) working in frame-transfer mode (1024 x 1024 image area) to avoid the need for a mechanical shutter. The CCD resides in the focal plane of a refractive system (Fig. 15) with an entrance pupil of ~50 mm and a field of view of 5.0 x 5.0 deg^2. It will be passively cooled by means of a radiator to an operational temperature range of -100 to -70°C. The complete system covers the wavelength range between 500 and 850 nm. A V-filter is included to allow for photometric calibration in a standard system. An optical baffle guarantees the necessary stray-light reduction for diffuse background. A once-only deployable cover mounted on a specially designed fore-baffle will protect the optics from contamination during ground and early in-orbit operations. The fore-baffle, besides accommodating the cover mechanism, will also protect the main baffle entrance from direct solar irradiation.

The CCD read-out electronics, residing in the OMC Electronics Unit, has multiple functions. On

Figure 13. Schematic of the Optical Monitoring Camera (OMC). The CCD sensing element is passively cooled to – 80°C (courtesy of LAEFF/INTA)

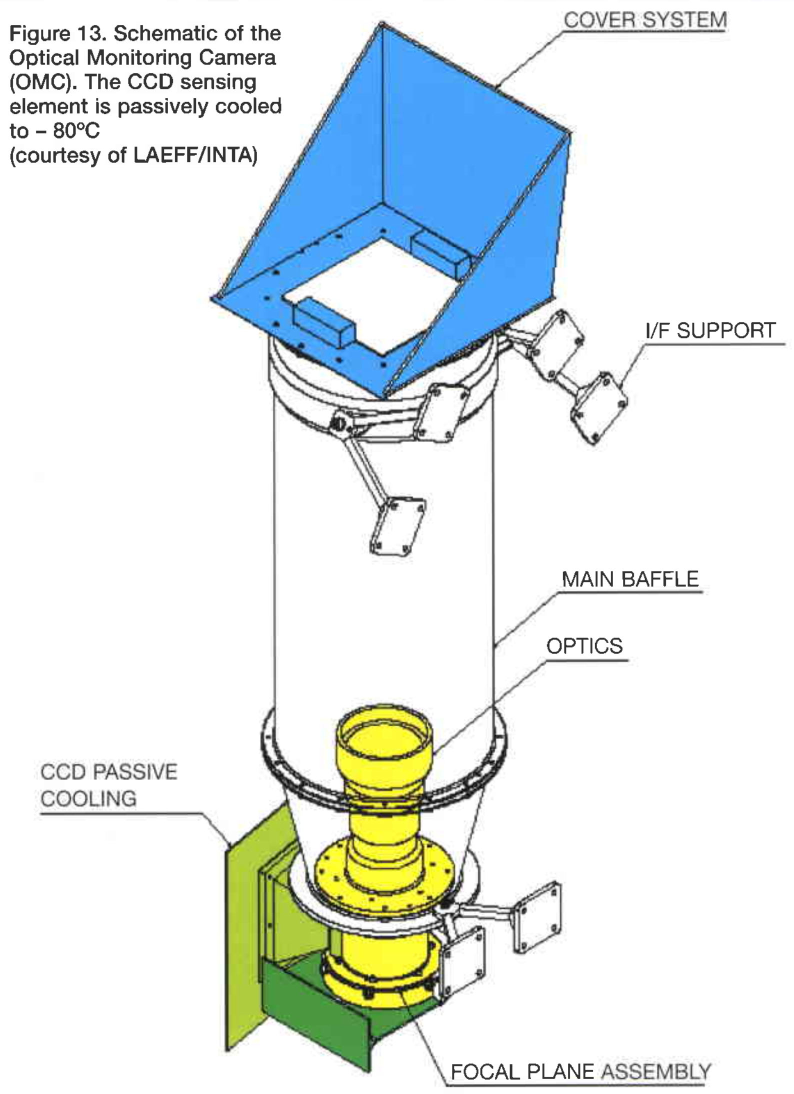
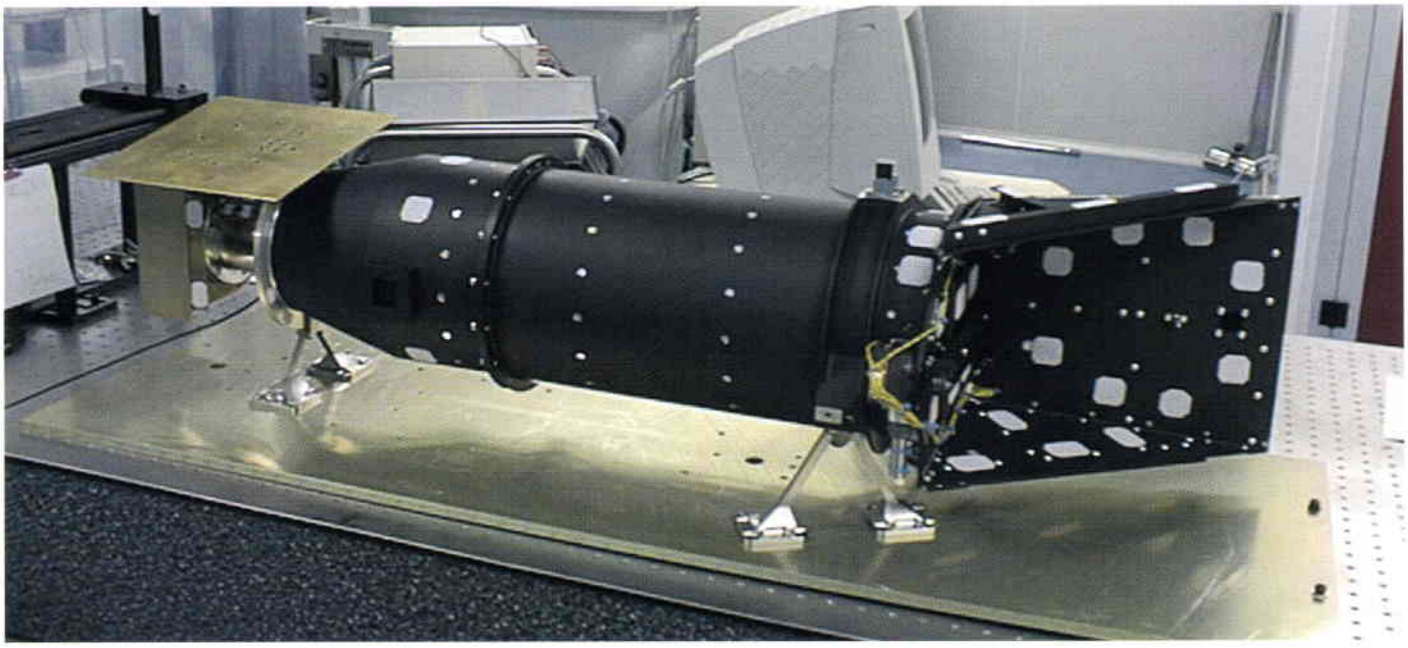


Figure 14. The OMC Camera Unit during its final acceptance testing. The square element close to the focal-plane region is the radiator for the CCD (courtesy of LAEFF/INTA)



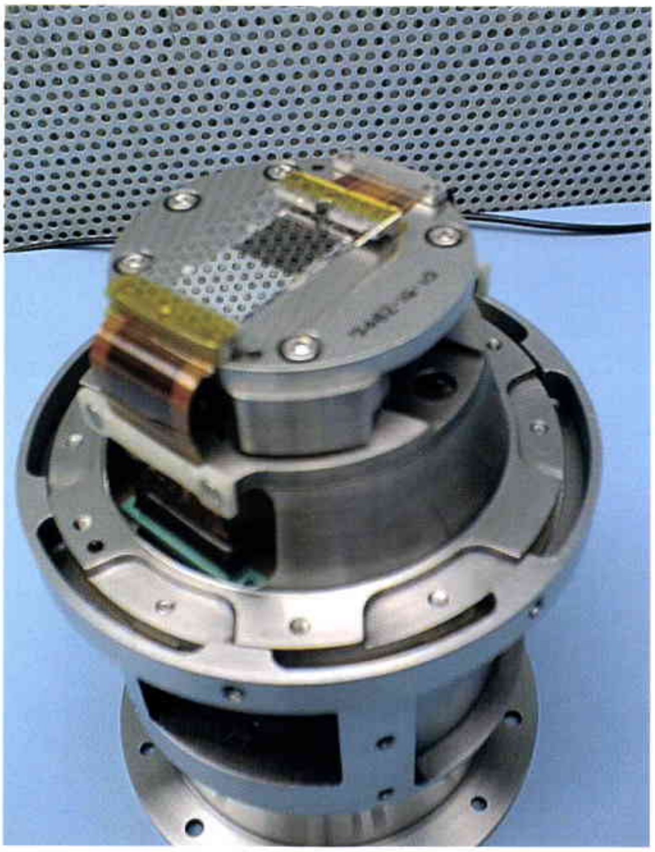


Figure 15. The OMC focal-plane assembly, showing the CCD at the top (courtesy of LAEFF/INTA)

the one hand it will control and command the CCD, and on the other it will digitise the read-outs and process the data for transmission to ground via the DPE and the spacecraft telemetry system. Within the CCD cavity of the camera, there are two LEDs for calibration purposes. When activated they illuminate the image area of the CCD. The differential response of each pixel to this known illumination pattern is used to build a flat-field correction matrix, which is needed for the photometric calibration of the images (ground processing). This system is intended to determine the relative quantum efficiency of each CCD pixel to an accuracy of better than 1% in a period of less than 1000 sec. New flat-field images will be taken with a periodicity of the order of CCD degradation once Integral is in orbit. For comparison, dark-current measurements will be performed using masked CCD pixels. Periodic dark-current measurements and flat-field images will also contribute to the absolute photometric calibration performed on the ground using the standard photometry stars imaged in 'Science Mode'.

During the nominal mission phase, scientific data will be acquired repetitively when the satellite is in a stable pointing mode. The OMC is then in its standard operating mode, called the 'Science' mode. The instrument does not provide images whilst the spacecraft is slewing, but is ready to accept new imaging commands for the next acquisition. In Science mode, the OMC will take images of the full field of view every 1 to 255 sec, depending on the integration times for the different targets. The baseline is to follow a given sequence of different integration times within these limits in order to monitor both bright and faint sources in the field of view. This sequence is configured just before the Science mode is entered, using a dedicated imaging command. The target stars are selected from a sky catalogue (the OMC Catalogue) using a software tool provided by the OMC team to the Integral Science Operations Centre.

Other operating modes for specific investigations are the Fast Monitoring sub-mode, which will allow the monitoring of rapidly variable sources down to 1 sec periodicity, and the Trigger sub-mode, which will allow the monitoring of new sources with a short response time.

Conclusions

Seven years after the kick-off of its design phase (Phase-B), the Integral satellite is now ready to fly. As confirmed by the recently concluded Instrument Flight Acceptance Review, the performances of the four payloads are as good or even better than those foreseen during the Phase-A study.

Acknowledgements

The authors wish to acknowledge the huge efforts of the Principal Investigators, the Instrument Project Managers, and their scientific and industrial teams. Thanks to their dedication and to the work of Alenia Spazio as satellite Prime Contractor, a new ship has been built to sail towards the new frontiers of astronomy.

The Integral Operational Ground Segment

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Integral will be launched in October this year by a Russian Proton rocket into a highly elliptical orbit. The mission will be controlled from the Integral Operational Ground Segment, which will take charge of the satellite's operation from its separation from the launcher until the end of the mission. This article describes the ground-segment architecture and specifically the functionality of the Integral Operational Ground Segment. The latter's design is based on the latest ESA infrastructure develpments in the fields of mission-control systems (SCOS 2000), station modulation, demodulation and tracking systems, and interoperability between ESA and NASA/JPL for cross-support of the mission.

The mission profile

The International Gamma-Ray Astrophysics Laboratory (Integral) is designed for two years of in-orbit operation, with the on-board consumables sized for a possible mission extension of a further three years. The Proton launcher will deliver Integral into a highly elliptical transfer orbit, similar to the final operational orbit, but with a lower perigee at 685 km. During the subsequent Early Orbit Phase, the spacecraft will be gradually injected into its final orbit by a series of manoeuvres performed using the on-board resources (fuel and thrusters).

Table 1. Integral operational-orbit parameters and supporting ground stations

Parameter	Operational Orbit
Apogee altitude	153 000 km
Perigee altitude	10 000 km
Inclination	51.6 deg
Argument of perigee	300 deg
Orbital period	72 hours
RP ground stations	ESA Redu
	DSN Goldstone
	ESA Villafranca (backup)
EOP ground stations	ESA Villafranca
	ESA Redu
	DSN Goldstone
	ESA Perth

The nominal operational orbit parameters for Integral are given in Table 1, together with the combination of ground stations planned to support the Routine Phase (RP) of the mission and the stations that will be used in the Early Orbit Phase (EOP).

The driving requirement in the selection of the ground stations to support the routine phase of the mission was that the satellite is to be operated in real time from the ground (no on-board data storage provided). The combination of the ESA Redu and DSN Goldstone ground stations will provide coverage of the complete operational orbit above the Earth's radiation belts (approximately 90% of the total orbit), i.e. the part of the orbit of scientific interest in which the on-board Instruments can be operated.

Integral is an observatory-type mission and as such will be operated based on a pre-planned command schedule for each orbit, containing all scientific observations and spacecraft operations activities to be carried out during the orbit. The command schedule will be automatically executed within the Integral Mission Control System at the Mission Operations Centre.

The ground-segment architecture

The mission's ground segment consists of two distinct elements: the Integral Operational Ground Segment and the Integral Science Ground Segment (Fig. 2). The former will be responsible for spacecraft and instrument operations throughout the satellite's lifetime, from its separation from the launcher until the end of the mission. The latter includes the Integral Science Operations Centre (ISOC) located at ESTEC, Noordwijk in the Netherlands, and the Integral Science Data Centre (ISDC) located at Versoix in Switzerland. The ISOC is responsible for planning the scientific utilisation of the satellite, based on inputs from the gamma-ray science community and taking into account the on-board instrument characteristics. The ISOC will also

Figure 1. The Redu Integral ground station: central monitoring and control position and IFMS racks

maintain a copy of the archive generated by the ISDC, thereby providing an additional interface to the science community for the distribution of the mission's scientific products.

The ISDC is responsible for the scientific processing of the satellite telemetry and for the archiving of the mission's scientific products and distribution to the science community. In addition, the ISDC will detect Targets of Opportunity (TOOs) and Gamma-Ray Bursts (GRBs) from the telemetry received in real-time from the Operational Ground Segment. TOO alerts will be provided to the ISOC for the possible re-planning of observations during the current or future orbits. GRBs are transient phenomena, which will be detected in real time from the incoming science telemetry and will automatically generate real-time commands to the satellite, for specific setting of the Optical Monitoring Camera (OMC), and real-time alerts to the science community, so as to allow additional specific observations using Integral and other space and/or ground-based observatories. The ISDC is supported by the Principal Investigator teams, who are providing instrument-specific software and expertise for processing of the received scientific data.

The Integral Operational Ground Segment

The main architectural elements of the Integral Operational Ground Segment (OGS) are the ground stations, the Mission Operations Centre (MOC), and the communications system. The OGS is the sole interface to the satellite; all commands to the spacecraft and on-board instruments are generated at the MOC, and all telemetry from the satellite (spacecraft and instruments, housekeeping and science telemetry) is received at the MOC and distributed within the Ground Segment as necessary.

In the nominal mission scenario, the OGS will take charge of Integral's operation 1 h 32 min after lift-off, when the satellite separates from the Proton upper stage, within visibility of the Villafranca (E) and Redu (B) ground stations. The OGS's role will terminate with the end of the mission.

The ground stations will acquire the satellite via the radio-frequency communications at S-band (2 GHz), and track it during its pass over the station. They constitute the front-end interface between the OGS and the satellite. It is through this interface that the commands received from MOC and processed at the ground station are modulated in accordance with the relevant ESA Standards, frequency up-converted and transmitted to the satellite. On the receiving side, the telemetry received from the satellite is frequency down-converted, demodulated, decoded and pre-processed at the station to extract its main components (satellite housekeeping and science telemetry virtual channels) before transmission to the MOC. In addition, the ground stations will measure the satellite range and range-rate. The measurement data will be sent to the MOC, where they will be used for satellite orbit determination and maintenance. During the Early Orbit Phase of the mission in particular, range and range-rate measurements are essential for the initial orbit determination and for the calculation and verification of the manoeuvres required to achieve the final operational orbit.

The MOC is the heart of the OGS. It is from the MOC that all satellite operations, remote operation of the ESA ground stations, and communication-network operations are performed. The main building blocks of the MOC are the Integral Mission Control System (IMCS), the Flight Dynamics System and the Integral Simulator.

The IMCS provides the functionality required for satellite operations, including the final step of the mission-planning process, satellite monitoring and control, and transmission in real-time of the received satellite telemetry to the ISDC, together with the appropriate auxiliary data. In addition, the IMCS provides the facilities required for handling the on-board software-maintenance activities and the short- and long-term archiving of telemetry, telecommand and auxiliary data. The archive will be regularly consolidated with the satellite playback telemetry received from the ground stations after the pass; the consolidated archive will be regularly dumped (in portions of 12 h) onto CD-ROMs, which are to be provided to the ISDC for scientific processing. Telemetry access to the archive is to be provided, for diagnostic purposes, to authorised external users (the ISOC and the satellite manufacturer) via the Internet.

A key element for the operation of the IMCS is the Operational Data Base (ODB). For modern satellites, with sophisticated on-board functionalities and increased on-board autonomy, the ODB becomes very large, and that for Integral contains more than 200 000 records. Powerful database editors are required to handle such massive amounts of data efficiently. These have been developed by the Integral Operations Team, based on commercially available software (Microsoft Access) and have been adopted for several future ESA missions (see article in ESA Bulletin No. 103). The IMCS is based on the SCOS 2000 infrastructure, the latest ESA development in the domain of mission-control systems.

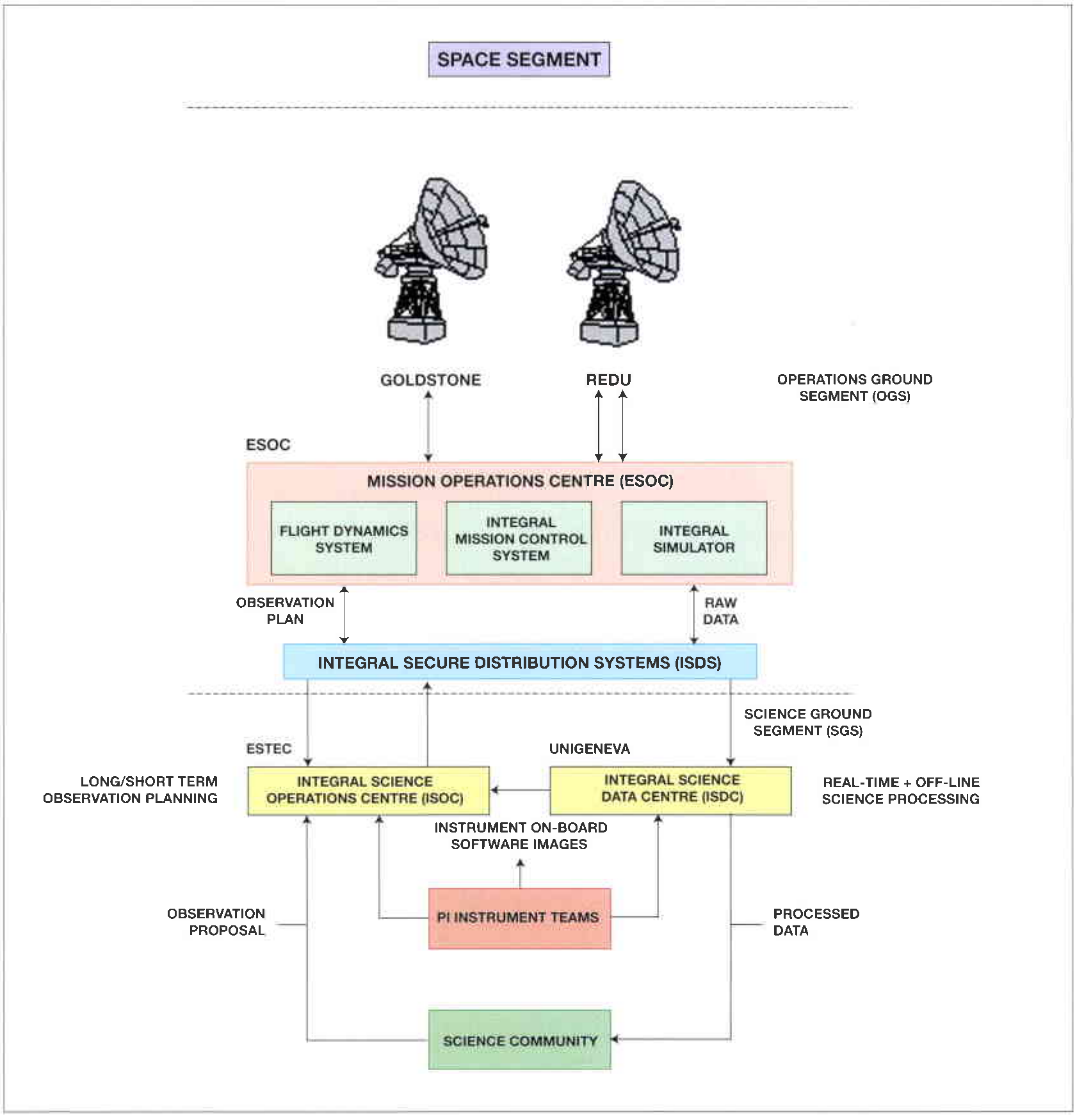
The Integral Flight Dynamics System (FDS) is based on the ESOC ORATOS infrastructure and provides the functionality required for satellite orbit and attitude determination and control, and for mission planning. On the orbit and attitude side, the system inputs are respectively range and range-rate (Doppler) measurement data received from the ground stations and the spacecraft telemetry from selected onboard subsystems (AOCS, RCS, star-trackers, fine star sensors, reaction wheels) received on-line from the IMCS. This telemetry is processed within the FDS on the basis of the FDDB (Flight Dynamics Data Base), which consists of a subset of the ODB enhanced with specific parameters characterising the satellite from a mechanical and dynamical point of view (distribution of masses, alignments, thruster specific impulse, etc.) provided by the satellite manufacturer and re-calibrated in flight. The attitude profile for the satellite throughout its orbit is determined at the mission-planning stage and is corrected in real time, as necessary, based on the telemetry being received. The FDS is also available in real time to the operator to provide any AOCS commanding information needed to handle contingencies.

On the mission-planning side, the FDS generates a Planning Skeleton File for each orbit, defining the windows for spacecraft operations and scientific observation. Once the file has been populated by the ISOC with the science observations to be conducted during the orbit, the FDS performs a final validation of the resulting product and converts it into a format suitable for the IMCS to derive the Command Schedule for that particular orbit.

The Simulator is an essential tool for system testing of the MOC components, including the interfaces to the other elements of the ground segment, for validation of the flight-operations procedures, and for pre-launch simulations and the training of the staff responsible for mission operations. It provides a realistic simulation of the ground stations and of the satellite's in-orbit functionality through accurate software modelling based on the Satellite Data Base provided by the satellite manufacturer. Figure 3 is a schematic of the MOC computer installation.

The OGS Communication System provides connectivity between the MOC and the ground station, and between the MOC and Science Ground Segment (ISOC and ISDC). It is based on leased lines interconnecting the various Integral ground-segment elements and

Figure 2. The Integral Ground Segment architecture



providing sufficient bandwidth to support the required operational traffic. Two protocols are used for communications within the Integral ground segment: the traditional protocol based on ISO X25 Recommendations for the operational communications between the MOC and the ESA ground stations, and the more modern TCP/IP protocol suite (as per RFCs) for the communications between the MOC and the Goldstone ground station and between the MOC and the Science Ground Segment.

State of the art elements in the Integral OGS

State of the art design has constantly been promoted within ESA in the Operational Ground Segments of ESOC-supported missions, and Integral is no exception. On the contrary, it is serving as the pilot mission for several new ground-segment infrastructure elements developed in parallel with the implementation of the Integral OGS. The pioneering work of the Integral OGS team in the extensive operational validation of these latest developments will be of significant advantage for future missions adopting similar infrastructures in their ground-segment designs. Three of the newly developed infrastructure elements used in the Integral OGS are described in more detail below.

The SCOS 2000-based Integral Mission Control System

SCOS 2000 is the latest ESA development in the field of Spacecraft Control Systems (SCOS) and Integral is the first science mission to exploit its full functionality and performance for its mission-control system. The IMCS has been build around the SCOS 2000 infrastructure, which comprises a telemetry chain for processing the satellite telemetry received through the ground stations, a generic telecommand chain, and an on-board software-maintenance subsystem for handling on-board memory images. This infrastructure has been complemented by additional software developments required to accommodate Integral-specific satellite design elements, both in the areas of telemetry and telecommand and ground-segment interfaces, and specifically those between the OGS and SGS.

Other SCOS 2000-provided functionalities have been adapted to best fit the satellite's operational requirements, as indicated in Table 2.

The highly distributed architecture of the IMCS-SCOS 2000 is based on the innovative SCOS 2000 concept of sharing the processing load within a family of servers. Specifically, the IMCS includes a main server where all of the kernel telemetry and telecommand functionality are provided, and a secondary server hosting the long-term archive, mission archive, archive consolidator and telemetry distribution to external users (SGS). IMCS-SCOS 2000 also has a modern and intuitive man/machine interface.

On the telemetry side, the main server performs the essential general-purpose processing (packet extraction and inclusion of headers with additional information); the telemetry is then distributed to the peripheral client work stations where the (configurable) part of the telemetry required by the specific application is processed. The main advantage of such a design is optimal usage of processing resources, and consequently increased system performance.

With Integral being the first SCOS 2000 client mission, during the IMCS's development and extensive testing, including operational validation, intense dialogue between the IMCS and the SCOS 2000 development teams has taken place, aimed at optimising the further releases of both systems. Significant effort has been devoted by the IMCS development team to system integration and configuration aspects, including failure and recovery analysis. This pioneering work will hopefully benefit future missions making use of the SCOS 2000 infrastructure for their ground segments.

Table 2. SCOS-2000 / IMCS functional mapping

Operational Data Base	**IMCS specific**
Telemetry Handling	
Telemetry reception (Packetiser)	IMCS specific
Telemetry processing	SCOS 2000
On-board events handling	IMCS specific
Telemetry displays	SCOS 2000
Variable packet display	SCOS 2000
Time correlation and stamping	IMCS specific
Telecommand Handling	
Command sender (Releaser)	SCOS 2000
Manual stack	SCOS 2000 enhanced with IMCS specific
Auto stack	SCOS 2000 enhanced with IMCS specific
Command verification	SCOS 2000 enhanced with IMCS specific
On-board queue management	SCOS 2000 enhanced with IMCS specific
On-board queue model display	IMCS specific
Infrastructure Services	
Short-term archive	SCOS 2000
Long-term archive	SCOS 2000 enhanced with IMCS specific
Time correlation	IMCS specific
Events and actions	SCOS 2000
Events logging	SCOS 2000
Task launcher	SCOS 2000
User-access management	SCOS 2000
OBSM Functionality	SCOS 2000 enhanced with IMCS specific
MPS Functionality	IMCS specific
External User Access	IMCS specific
File Transfer Service	IMCS specific
Data Distribution	SCOS 2000 enhanced with IMCS specific
Performance Analysis	SCOS 2000 enhanced with IMCS specific
Mission Archive	IMCS specific
Archive Completeness Checker	IMCS specific
CD-ROM Production	IMCS specific

The Intermediate Frequency Modem System (IFMS)

At the beginning of its main development phase (Phase-C/D), the Integral mission was the subject of several trade-offs. These were targeted on the one side at optimisation of the satellite's orbit, taking into account both the Proton launcher's performance and the scientific mission requirements, and on the other at maximising the telemetry allocation to the various on-board instruments for scientific-return purposes. Ultimately, this has resulted in a high bit rate (92 kbps) being transmitted over a large distance (orbital apogee: 153 000 km) via the radio-frequency link, keeping the on-board modulation scheme and the transmitter output power unchanged in terms of its inheritance from the XMM mission design. This results in the modulation characteristics of the received signal (in terms of carrier suppression) being at the limit of the performance specified for the standard receivers and demodulators in the current ESA ground-station network. The decision was therefore taken to adopt for the main Integral support ground station (Redu), the IFMS, at that time under development, which had a performance specification compatible with Integral's requirements.

The IFMS integrates into a single unit the functionality of the station receiver, including diversity combination, the tracking subsystem for satellite range and range-rate measurement, the remnant-carrier and suppressed-carrier demodulator (the latter not

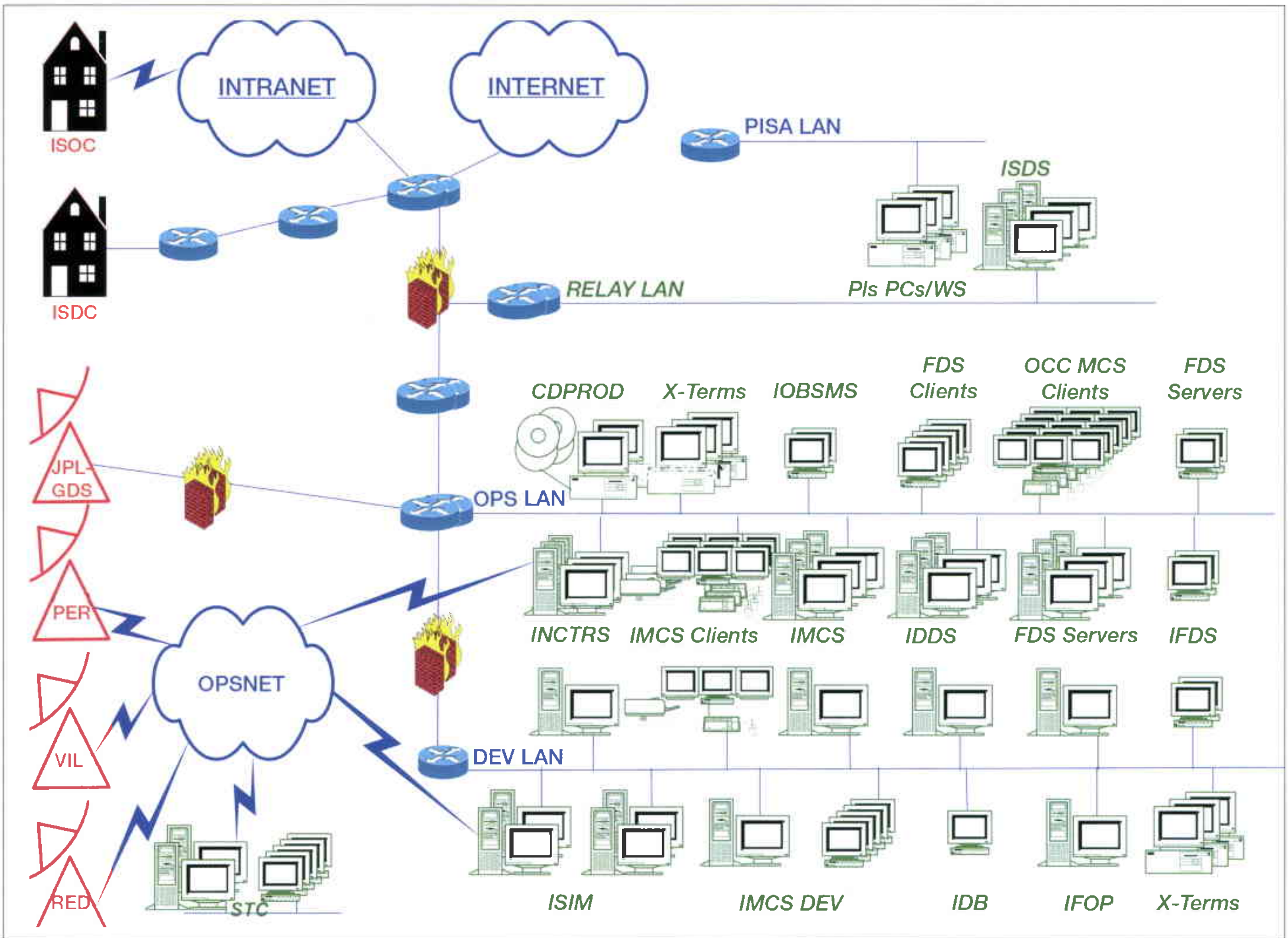


Figure 3. The Integral Mission Operations Centre computer-system configuration

applicable to Integral), and finally the uplink modulator. The system is based on three newly developed modules: a front-end module interfacing at the station intermediate downlink frequency (70 MHz) and sampling at 280 Msample/s, a number of Generic Digital Signal Processing (GDSP) modules implementing the demodulation and ranging functions, and a digital modulator module including digital-to-analogue conversion and up-conversion to the station uplink intermediate frequency (230 MHz). Subsystem control and auxiliary functions (time code reader, interface to the station monitoring and control computer, etc.) are largely based on commercial off-the-shelf products. The GSDP modules make use of Field Programmable Gate Arrays (FPGAs) which, still executing as conventional digital gates, can be programmed in software to implement the specific functionality allocated to the module. A particular feature of the IFMS is its suitability for remote operation and/or maintenance through the so-called 'Development Control Position'. This uses the Internet as the communication protocol and provides a web-browser-based interface, allowing remote control and/or maintenance of the IFMS system via the web.

The IFMS has undergone several tests in the context of the Integral Radio-Frequency Compatibility Tests and has also been validated in-flight on the Cluster and XMM missions as part of the Integral system validation process.

The Space Link Extension (SLE) services for Integral cross-support

The NASA/JPL ground station at Goldstone (Calif.) will be used to cross-support Integral for approximately 20% of its operational orbit above the Earth's radiation belts. For past missions, inter-Agency cross-support has always been dealt with in an ad-hoc manner through mission-specific arrangements involving the exchange of equipment, or mission-specific designs for gateways in order to adapt the interfaces between the ground-segment elements involved in the cross-support (ground stations and/or control centres).

The inefficiency of this way of operating was recognised some years ago by the Consultative Committee for Space Data Systems (CCSDS) which, through its Panel 3, has developed a Cross-Support Reference Model from which the recommendations for the SLE services, aimed at providing a uniform cross-support capability within the CCSDS member agencies, have been derived.

The Cross-Support Reference Model was published in a CCSDS Blue Book in May 1996 (ref. CCSDS 910.4-8-1). That same year, the Integral Project and JPL agreed on an initial SLE services development for the cross-support by the Goldstone station of the Integral mission. That agreement was endorsed at agency level by ESA and NASA in 1997. The basic set required for Integral operation, i.e. Return All Frames (RAF) and Return Virtual Channel (RVC) on the Return Link (telemetry) side and Forward Space Packet (FSP) on the forward-link (command) side, was defined and the development work was started both at ESOC and JPL. At the Plenary ITCOP meeting in Paris in 1998, at which 7 CCSDS member agencies were represented, CLTU was selected for the forward-link service instead of FSP, for reasons of compatibility with legacy systems still present in some ground-station networks.

The SLE services design contains three key elements: the Transfer Service Application and Protocol specified in the CCSDS Recommendation applicable to the service concerned; the Application Programming Interface, a generic design able to accommodate a variety of communication middleware technologies, and supporting both service provider and service user functions; and finally the Service Management, which includes the exchange of trajectory-prediction, scheduling, resource-allocation and operations-control procedures. The parallel ESOC and JPL development work was completed at the beginning of 2001 and the services have subsequently undergone extensive progressive testing in the Integral context, starting from a back-to-back testing of the application for each service, and continuing through trans-Atlantic testing between the Integral MOC and JPL/Goldstone, until their recent final validation including the service-management functionality.

Conclusions

The distributed architecture of Integral Ground Segment has been presented, with the focus on the functionality of the Operational Ground Segment (OGS), in which state-of-the-art design has been applied. In particular, three new major infrastructure developments – the main design features of which have been presented here – are being used for the first time to support the operation of a demanding ESA scientific mission. The OGS has undergone an extensive testing programme to validate its functionality and interfaces to the other Integral Ground Segment elements (ISOC and ISDC), and is now ready to support the Integral mission.

esa

Integral – Running the ESA Gamma-Ray Observatory

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This article provides an overview of the planned Integral mission operations, focussing on the role of, and activities to be performed by the Mission Operations Centre (MOC). It identifies ground-segment elements involved in the various operations and the operational concepts underlying the different Integral mission phases. Finally, a short overview of the current status of the mission-operations preparations is given, including the system test activities.

The goals

Integral's contribution to astrophysics will be the observation of various gamma-ray phenomena by combining fine spectroscopy with imaging and accurate positioning of celestial sources of gamma-ray emission. It will also have the capability of simultaneous monitoring at other wavelengths, namely the X-ray and optical bands. In conducting this unique scientific mission, several observation patterns will be applied:

- *Deep exposures of the central Galactic Radian:* Individual pointings on a regular grid with 2.4 and 1.2 deg spacing will cover the core of the our Galaxy (± 30 deg in longitude, ± 20° in latitude). Each such exposure will take 30 minutes.

- *Survey of the Galactic Plane:* A survey will be made of weekly scans following a saw-tooth path to search for as yet unknown persistent sources – such as recent galactic super-novae – and to map our Galaxy's gamma-ray emission. Each scan will consist of a series of individual exposures of 1050 sec duration. The pointing attitude will be separated by 6.0° along the scan path (Fig. 1).

- *Staring observations:* Extended periods of stable pointing will be used to study faint sources and phenomena that are variable in time.

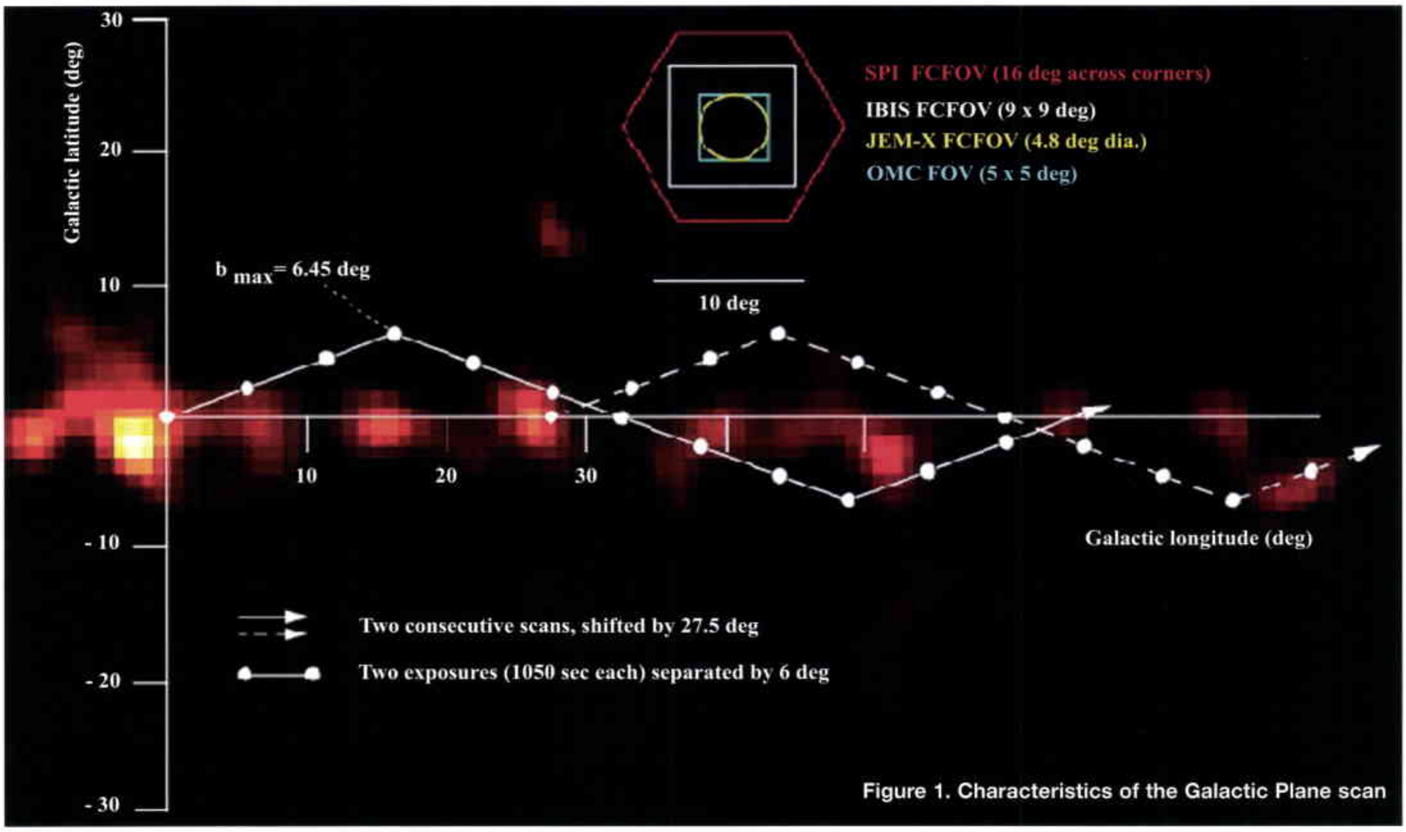

Figure 1. Characteristics of the Galactic Plane scan

Another facet of the mission concerns Gamma-Ray Bursts (GRBs). Integral's instruments and ground segment will allow the identification of GRBs and the provision of key data to the scientific community in near-real-time. Not surprisingly, these mission goals have had a significant influence on the ground-segment set-up and the way in which the Integral operations will be conducted.

The ground-segment elements

Like other observatory missions, Integral can only meet its ambitious scientific goals with the support of its dedicated ground segment. The in-orbit operations are reliant on complex interactions between the various ground-segment elements, which essentially fall into two parts:

- the Operational Ground Segment (OGS) and
- the Science Ground Segment (SGS).

The OGS is responsible for all mission operations, including platform and instruments, and consists of:

- the Mission Operations Centre (MOC)
- the ground stations (Redu in Belgium, and Goldstone in California) and
- the operational network.

The SGS covers all scientific aspects of the mission and itself consists of two components:

- the Integral Science Operations Centre (ISOC), and
- the Integral Science Data Centre (ISDC).

The structure of the complete Integral ground segment and its interfaces is illustrated in Figure 2.

The Mission Operations Centre (MOC) is located at the European Space Operations Centre (ESOC), in Darmstadt, Germany. The MOC is the sole interface to the satellite and is responsible for monitoring and controlling it during all mission phases, following its separation from the Russian Proton launcher. Once the satellite has been commissioned, all operations will be executed according to

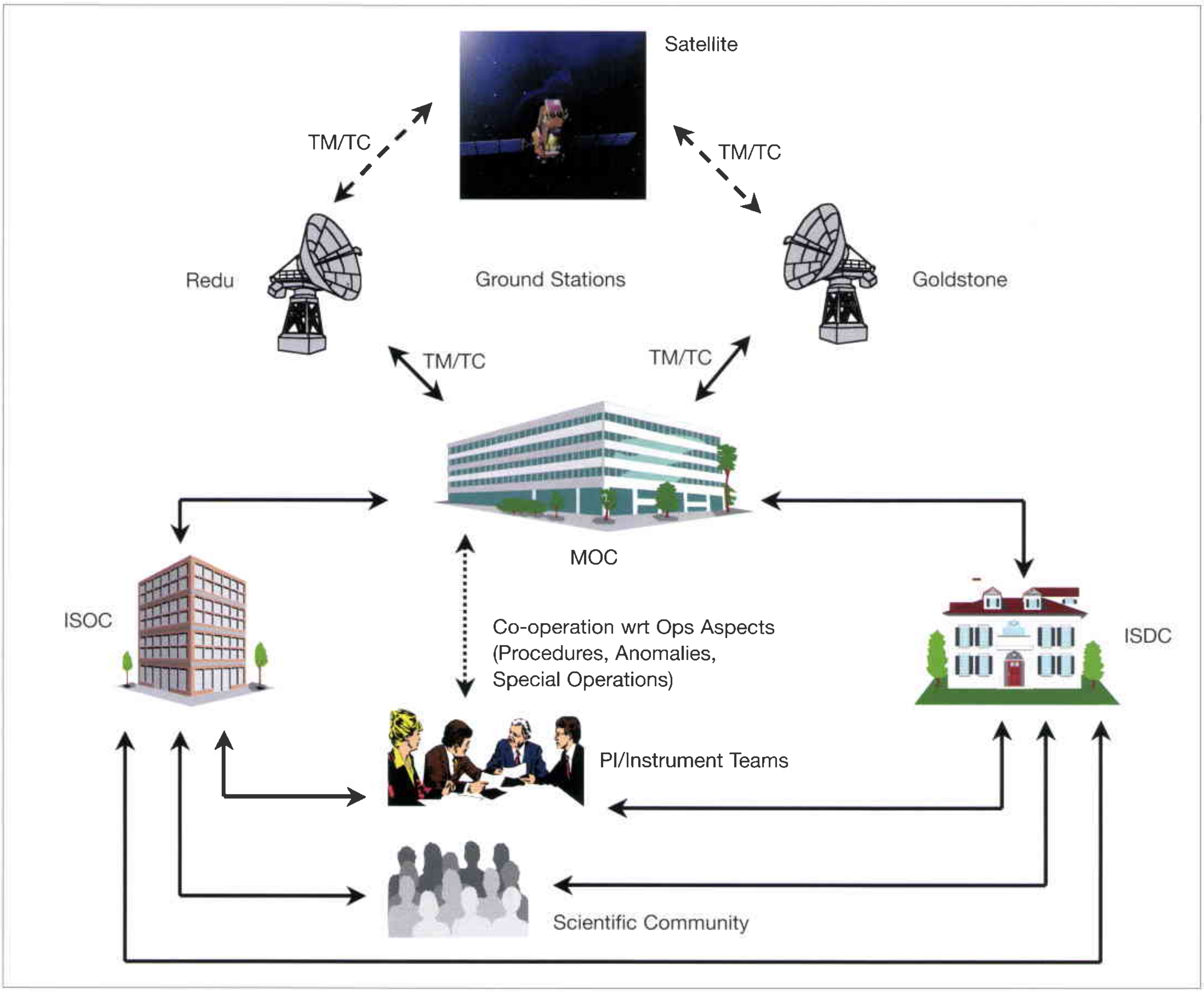

Figure 2. The configuration of the Integral Ground Segment

operational timelines, each segment of which covers a full three-day orbital revolution and is produced by the MOC based on planning inputs provided by the Integral Science Operations Centre (ISOC).

The ISOC is located at the European Space Research and Technology Centre (ESTEC), at Noordwijk in The Netherlands. It is mainly responsible for the collection of the observation requests from the scientific community and the generation of the observation plan that drives the utilisation of the Integral payload.

The Integral Science Data Centre (ISDC) is located in Versoix, near Geneva (CH) and is a non-ESA institution. It is mainly responsible for the processing of the science data - including the maintenance of the scientific archive - and the generation and distribution of the scientific products.

The Integral satellite has only limited on-board time-tag command capabilities, and so this capacity is used only for safety aspects. Since Integral is to be controlled in real-time from the ground, a network of stations has been implemented that allows permanent contact with the satellite during the scientifically useful part of the orbit. The two primary ground stations are located at Redu in Belgium, which is a station provided by ESA, and at Goldstone in California (USA), which is a station provided by NASA/Jet Propulsion Laboratory (JPL).

A communications network has been set up under ESOC's responsibility which ensures communication between the various centres and between the MOC and the ground stations.

Figure 3. The Integral Dedicated Control Room during System Validation Test activities

The MOC's role

The Integral Mission Operations Centre will be responsible for all mission operations. This covers the preparation and execution of operations during:
- the Launch and Early-Orbit Phase (LEOP)
- the Satellite Commissioning Phase, and
- the Routine Mission Phase.

The individual tasks include:
- provision of a Planning Skeleton File (PSF) to the ISOC
- generation of the operations timeline
- execution of all satellite operations
- execution of platform and instrument maintenance operations
- monitoring of satellite (spacecraft and instruments) safety and health
- determination and control of the satellite's orbit and attitude
- maintenance of the satellite's on-board software
- provision of telemetry and auxiliary data to the ISDC.

In order to perform the above tasks, the MOC relies heavily on the existing ESOC infrastructure, including the control rooms, communications facilities, and computer hardware. The most intensive use of these facilities will be made during the Launch and Early-Orbit Phase (LEOP), as this is the most critical period of the mission and thus the most demanding in terms of resources (facilities and manpower). The LEOP operations will mainly be performed from ESOC's Main Control Room (MCR) and Flight Dynamics Room (FDR). The Routine Mission Phase operations will be conducted from the Integral Dedicated Control Room (DCR); see Figure 3.

The Flight Control Team (FCT) is responsible for all mission operations. Led by the Spacecraft Operations Manager, it consists of:
- an engineering team: five engineers who are responsible for controlling and monitoring the satellite subsystems, the on-board software maintenance, the mission planning and the preparation/execution of the operational time-lines
- a spacecraft-analyst team: two analysts who are responsible for the maintenance of the Operational Database and other operational tools, and also support the engineering team
- a spacecraft-controller team: six controllers who are responsible for the routine operation of the satellite.

Various other ESOC personnel support the FCT during the different mission phases, not only in terms of optimally exploiting the ESOC internal infrastructure (communications, computer hardware/software, etc.), but also in monitoring and controlling the external communications and the ground stations. The ESOC-provided infrastructure also includes the Integral Mission Control System (IMCS), based on the generic SCOS 2000 system, and the Integral Flight Dynamics System (IFDS), based on the existing ORATOS infrastructure. The ESOC Flight Dynamics Team has been an important contributor to the mission planning for the satellite and its attitude and orbit control philosophy.

The LEOP and Commissioning Phases

The satellite has been transferred to the Baikonur launch site about two months before launch. Communications links with Baikonur will allow the pre-launch activities to be followed from ESOC. ESOC is providing facilities to accommodate teams from the Principal Investigators (PI), the spacecraft manufacturer and the Project from three months before until three months after the launch. It will also allow the Instrument teams to analyse their instrument data from ESOC during the Integral Commissioning Phase.

The critical Launch and Early Orbit Phase activities will start in earnest about 8 hours before launch. The MOC will remain in contact with the satellite until the launch, but during the launch phase itself no link will be available to the satellite. The next contact with the satellite will be established via ESA's Villafranca (E) ground station about 10 minutes before Integral's separation from the Proton launcher. A few minutes later, the Redu (B) ground station will also make contact with the satellite, and both stations will be used to support the post-separation operations. At separation, the MOC will establish the command link and will monitor the activation of the satellite.

The initial in-orbit phase will last about 6 h, ending with the transition into the Inertial Pointing and Slew (IPS) mode. At this point the spacecraft platform will be fully activated and the satellite in a stable pointing state. The following days will be devoted to checking-out all platform subsystems and the activation and check-out of the scientific instruments.

As the launcher does not deliver the satellite directly to its final operational orbit, perigee-raising burns will be conducted using Integral's on-board thrusters at the apogees 3, 4 and 5. As soon as the last manoeuvre has been performed, the verification of instrument performances will commence, which will last until two months after the launch. When all checks have been successfully completed, the satellite will be declared operational and the Scientific Mission phase can begin.

The operations concept and its implementation

For the Integral mission operations to be conducted safely and efficiently, several critical constraints have to be respected, typical examples of which are summarised in Table 1. All such constraints had to be considered at the planning stage to arrive at an operational timeline that can be executed safely.

Table 1. Mission constraints

Pointing	The star-tracker bore sight shall be no closer than 15 deg to the Earth's limb and separated by at least 10 deg from the Moon's limb.
Wheel Speeds	The wheel speeds shall not exceed specified limits and shall be outside the zero-speed region (± 120 rpm)
Solar Aspect Angle (SAA)	The SAA shall be less than 40° (30° when the power supply from the solar array is degraded) for power reasons.
Roll Angle	The roll angle is to be less than 5° for thermal reasons.
Slews	Several constraints have to respected here, e.g. a max. slew speed, to ensure proper slew performance.

The routine mission operations are preceded by comprehensive mission-planning activities. About 6 months before the execution of operations, the MOC provides requests to NASA/JPL regarding utilisation of its Goldstone station. The next step concerns the generation of the skeleton plan needed by the ISOC to plan the observations. The Flight Dynamics Team generates a set of Planning Skeleton Files (PSF) covering a one-month period, about one month in advance. Each PSF concerns one orbital revolution and identifies the time windows that are available for science operations. The PSFs are provided to the ISOC, which uses them to prepare the Preferred Observation Sequences (POS). Each POS identifies the required pointings and the corresponding instrument configurations for a single orbit.

A set of five POS is provided about two weeks in advance to the Flight Dynamics Team, which enhances them by including the necessary satellite operations, in particular the inputs needed to control the spacecraft's attitude. The products of this activity are the Enhanced Preferred Observation Sequences (EPOS).

The EPOS are provided to the FCT, which then generates the Operational Timelines, which are the reference for the generation of the command schedule. The Timeline for a satellite revolution is available one week in advance to Operations. A Timeline summary is sent to the ISOC for confirmation.

An overview of the main planning activities is shown in Table 2.

The command schedule will be loaded during the satellite's perigee passage before the orbital revolution concerned. The commands will be executed automatically by the command system, and manual commanding is only envisaged under special circumstances. The same is true for on-board time-tag commands, which are only used to execute operations that are to be performed outside ground coverage, e.g. during eclipse and perigee passages. The Spacecraft Controller on shift monitors the operations and the safety/health of the platform and instruments.

All telemetry and auxiliary data (e.g. attitude data or operations log) needed to evaluate the scientific data are provided to the ISDC in real-time. The data are further processed by the ISDC and used for a quick assessment of the science. If necessary, the ISDC will send requests for an update of the instrument configuration to the ISOC. Subject to the ISOC's approval, the requested replanning will be started, and the turnaround time for such an activity will be less than 36 h. The consolidated telemetry data are provided by the MOC to the ISDC (on CD-ROM) within some days after a particular orbit's completion. They will be used to generate the appropriate scientific products for onward distribution to the scientific community.

Implementation of the operations

The Integral mission has very particular requirements in terms of satellite attitude control, which call for some special functions within the MOC. Because its main instruments use masks to suppress background radiation effects, Integral must slew frequently around the target in order to monitor the sources from various angles. In addition, the mission's scientific objectives include systematic monitoring of the sky. These demands lead to various types of observation patterns:

Hexagonal Dither Pattern
- Hexagon around the nominal source location, i.e. 7 pointings (a number of cycles can be observed together)
- Closed-loop slew of 2° between two pattern points
- Duration of each pointing 30 min.

Raster Dither Pattern
- m x n raster around the target, i.e. m x n pointings (a number of cycles can be observed together)
- Closed-loop slew of 2° between two pattern points
- Duration of each pointing 30 min.

Galactic-Plane Survey
- Saw-tooth path along the Galactic Plane with an inclination of 21° (arcs covering a subset of the Galactic Plane will be observed together)

Table 2. Overview of the main mission planning activities

Time	Activity	Initiator	Data Product	Remarks
T0 – 6 months	Long Term Planning	MOC/FD	Long-Term Event Plan	
T0 – 6 months	Goldstone Scheduling Request	MOC/SO	Schedule Request	Period of 6 months covered, 6 months in advance
T0 – 1 month	Generation of PSF Provision of PSF to ISOC	MOC/FD	Planning Skeleton File	Period of 1 month covered, 1 month in advance
T0 – 2 weeks	Generation of POS Provision of POS to MOC	ISOC	Preferred Observation Sequence	Period of 2 weeks covered, 2 weeks in advance
T0 – 2 weeks	Processing of POS & generation of EPOS	MOC/FD	EPOS	Period of 2 weeks covered, 2 weeks in advance
T0 – 1 week	Generation of Operational Timeline	MOC/FCT	Operations Timeline	Period of 1 week covered, 1 week in advance
T0 – 3 days	Generation of Command Schedule	MOC/FCT	Command Schedule	Period of 1 orbit, 1 orbit in advance
T0	Start of Operations			

- Open-loop slew of 6 deg between two pattern points
- Duration of each pointing 1050 sec.

Galactic-Centre Radian Deep Exposure
- 21 x 31 pointings raster, i.e. 651 pointings (selected subsets will be observed together)
- Closed-loop slew of 2° between two pattern points
- Duration of each pointing 30 min.

The above observation patterns require the execution of a slew manoeuvre typically every 30 min. An important feature to be considered in this context is that the nominal operations are to be performed in a gyroless manner, which has implications for both the open- and closed-loop slews.

Closed-loop slews can be performed when the slew angle is such that the guide star remains within the Field of View (FOV) of the star tracker. The advantage of this type of slew manoeuvre is that the accuracy of the pointings remains within very strict limits. Open-loop slews are to be chosen in the case of bigger slew angles, considering the various constraints applicable, such as the maximum slew speed.

The accuracy of the pointing after an open-loop slew depends on the duration of the manoeuvre. Since a sequence of several open-loop slews can lead to an increasing attitude inaccuracy, a real-time attitude reconstruction is performed by the Integral Flight Dynamics System (FDS). The IFDS determines the deviations from the planned attitudes and provides corrections for the upcoming slews to the Mission Control System (IMCS), in a fully automated process. The Integral File Transfer System (IFTS) takes care of the transfer of files between the IFDS and the IMCS.

Depending on the observations planned, there may be more than 100 slews during a single revolution. Since the satellite is controlled using reaction wheels, the momentum is to be carefully determined in order to perform momentum dumps at the appropriate times. The FDS determines an adequate momentum profile (Fig. 4) for each revolution at the planning stage. Regular checks are performed to ensure that the actual wheel speeds do not deviate significantly from those planned, otherwise the on-board Autonomous Momentum Dumping (AMD) mechanism will be triggered for safety reasons when the allowed wheel-speed boundaries are breached.

Apart from the AOCS operations, the MOC also controls the platform's on-board subsystems (power, thermal, on-board data handling, etc.) as well as the various instruments.

The platform operations are planned and executed solely by the MOC. The instrument-related operations are a shared activity between the MOC and ISOC. While the ISOC plans the instrument configurations that are relevant for the various observations, the MOC plans the routine instrument operations that are required during an orbit. The operations planning is done using the so-called 'Event Designators' (EDs), which are keywords put by Flight Dynamics into the planning files to identify the appropriate command activities.

Integral's instruments require a lot of routine operations because they have to be put into a safe configuration for each perigee and eclipse passage. The platform-related operations are less complicated. Its thermal subsystem does not require a lot of ground intervention because most of the thermal-control cycles are implemented on-board. The power subsystem requires some eclipse-related operations, such as battery charging. These operations can be pre-planned, which is also true for the On-Board Data Handling (OBDH) subsystem, including the selection of the appropriate antenna depending on satellite attitude and station visibility. The FDS pre-integrates the corresponding EDs into the EPOS.

The MOC is also responsible for the On-Board Software (OBS) and conducts a regular assessment of satellite functions and performance to identify any needs for OBS upgrades.

The MOC processes only the satellite housekeeping data. The processing of the science data is the task of the ISDC. The MOC performs a pre-processing of the telemetry received from the various ground stations and provides it, together with some ground-reception-time and data-quality annotations, to the ISDC. To generate the science products, however, the ISDC also requires information about the satellite's attitude and the execution of the operations, which is provided in form of auxiliary data files by the MOC in near-real-time.

Operations preparation status

At the time of writing, the development and testing of the ground segment has been largely completed and the simulation campaign is in progress. In addition to the testing at subsystem level, many system tests have been conducted, including the System Validation Tests (SVTs) involving the flight-model satellite. These SVTs focused on the validation of the MOC functions and operational procedures, as

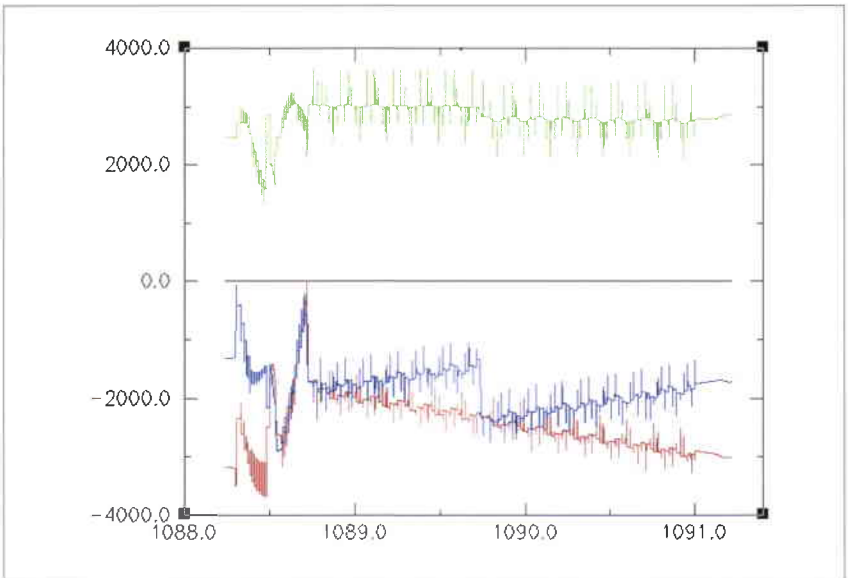

Figure 4. A typical profile for momentum wheels 2, 3 and 4 during a single satellite orbit. The x-axis indicates the days (reference is 1 January 2000), and the y-axis the wheel speeds in rpm

well as providing a platform for performing the overall ground-segment end-to-end tests, involving the ISOC and ISDC. The latter, together with the Ground Segment Integrated Tests (GSITs) form the main basis for validating the overall Integral Ground Segment. All SVTs and GSITs performed so far have been successfully completed and the test goals were fully achieved. The main results of the system test programme are:

- validation of the functions of the Mission Control System
- validation of the interfaces from/to the Mission Control System
- validation of the overall Ground Segment Operations Concept and Interfaces
- verification (*no complete validation*) of the Operational Database
- verification (*no complete validation*) of nominal flight procedures
- verification (*no complete validation*) of major flight-contingency procedures.

The ongoing work related to the preparation of the mission operations mainly concerns the consolidation of the Flight Operations Plan (FOP) and the Operational Database (ODB) and the training of the operations teams.

Acknowledgments
We wish to thank the various support teams at ESOC for their support during the various phases of preparation for the Integral mission. We would also like to thank the other Integral teams at the ISOC and the ISDC for their cooperation and support.

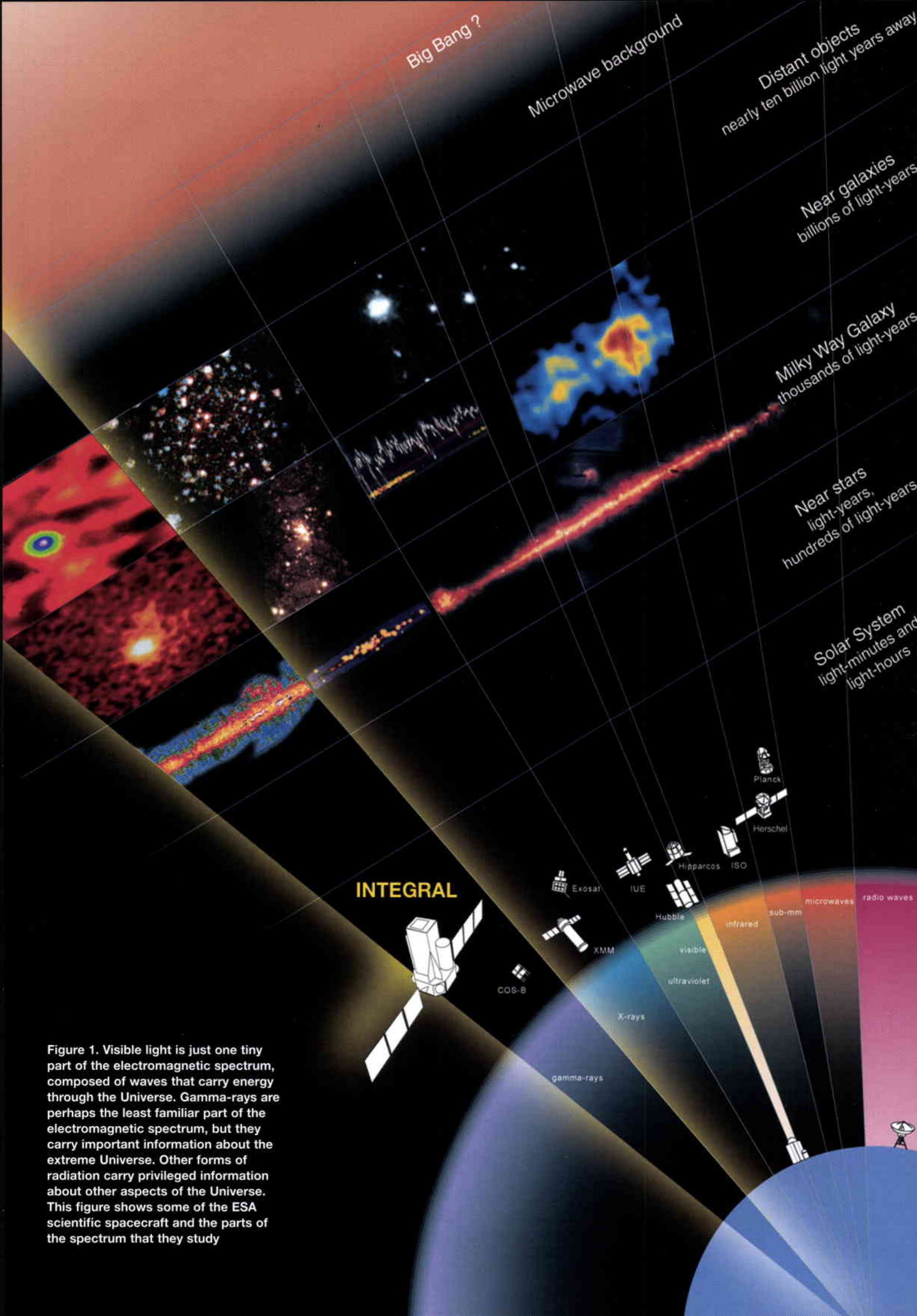

Figure 1. Visible light is just one tiny part of the electromagnetic spectrum, composed of waves that carry energy through the Universe. Gamma-rays are perhaps the least familiar part of the electromagnetic spectrum, but they carry important information about the extreme Universe. Other forms of radiation carry privileged information about other aspects of the Universe. This figure shows some of the ESA scientific spacecraft and the parts of the spectrum that they study

The Integral Science

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The Integral mission will provide a view of the Universe very different from what we see when we look skyward on a clear night. Instead of the familiar stars that shine steadily from night to night, Integral will reveal a violent, highly variable Universe in which intense new sources can suddenly appear, emit almost unbelievable amounts of energy and then disappear, sometimes never to be seen again. Integral's task will be to collect gamma-rays, the most energetic radiation that comes from space, to allow astronomers to study such bizarre objects as black holes, neutron stars – objects so dense that a teaspoon full would weigh millions tonnes here on Earth – and the mysterious gamma-ray bursts, which may be signalling the explosive deaths of massive stars. All of these objects release vast amounts of energy, much of it in the form of gamma-rays. Integral, together with ESA's recently launched XMM-Newton X-ray observatory, is set to substantially improve our understanding of the turbulent Universe.

Introduction

Gamma-rays are even more powerful than the X-rays used in medical examinations. In fact, it would take about a million rays of visible light to match the energy of a single gamma-ray. Fortunately, gamma-rays from space cannot reach the ground because they are blocked by the Earth's atmosphere. This is why Integral has to observe from space, but even from here the task is very difficult because gamma-rays easily pass straight through the mirrors and cameras of normal telescopes. Instead, Integral will use two specially designed gamma-ray telescopes to register these elusive rays.

One telescope, the Spectrometer on Integral (SPI), will measure their energy very precisely, while the other, the Imager on Board the Integral Satellite IBIS), will provide very fine images. Together with the Joint European X-ray Monitor (JEM-X) and the Optical Monitoring Camera (OMC), all of the Integral instruments will observe the same region of sky at the same time. It will be a prime task of the astronomers who are going to use Integral to combine the measurements made with the different instruments in the best possible way to allow the overall properties of the gamma-ray sources to be studied.

Integral will continue the strong European tradition in gamma-ray astronomy that started with ESA's COS-B satellite in 1975. This was followed by the Russian-French mission GRANAT (1989-1998) and NASA's Compton Gamma-ray Observatory (1991-2000), to which European institutes contributed. The international High-Energy Transient Explorer satellite (HETE-2) was launched in 2000 and includes a French gamma-ray telescope and X-ray detectors. Soon, astronomers all around the World will have Integral, the most sensitive gamma-ray observatory ever.

Here we describe some of the key scientific objectives of Integral, present the first year's observing programme and describe the organisation of the scientific component of the ground segment.

Integral science objectives

Super-dense stars

When a massive star explodes, not all the material is ejected into space. Some of it can collapse into an extremely compact object known as a neutron star. A neutron star is only the size of a city, but may contain as much material as two or three stars like the Sun. It is no wonder that neutron stars are incredibly dense – a teaspoonful of neutron star 'stuff' would weigh millions of tons here on Earth! Some neutron stars have incredibly strong magnetic fields due to the original star's magnetic field being 'trapped' and concentrated during the collapse. As they spin, these magnetic neutron stars may emit strong radio pulses and are known as 'pulsars' (Fig. 2). If such magnetic neutron stars are located in

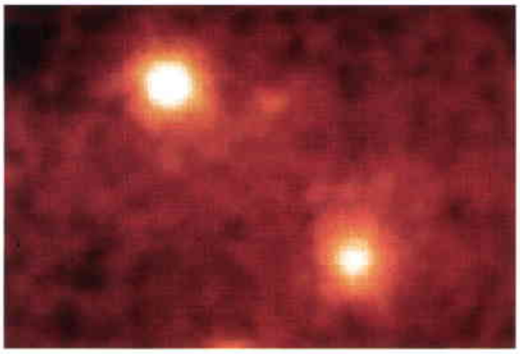

Figure 2. A gamma-ray view of a region of sky containing two spinning neutron stars or pulsars (the Crab and Geminga) and strong diffuse emission. It was taken with NASA's Compton Gamma-ray Observatory (courtesy of NASA)

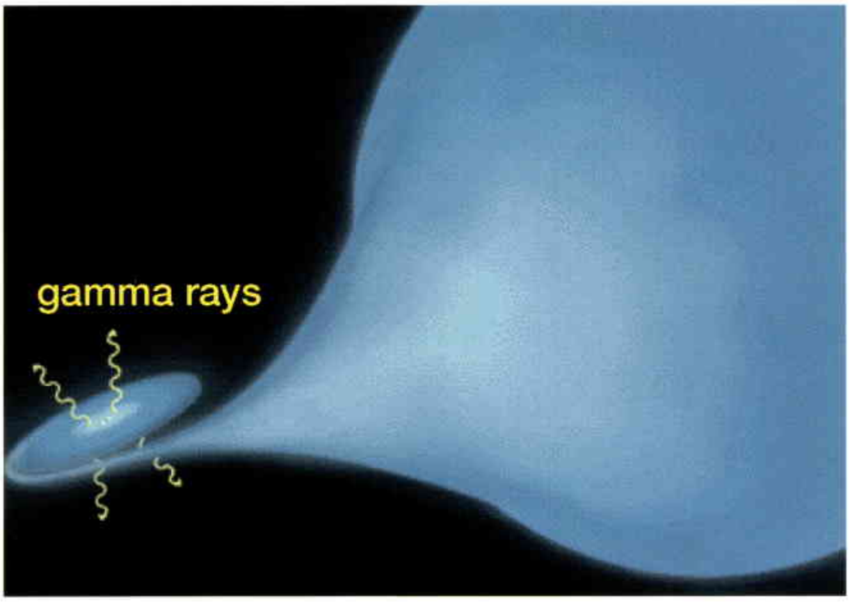

Figure 3. Artist's impression of an accreting binary system, in which material is falling onto a compact object such as a black hole or neutron star from the companion star, shown on the right of the picture. The companion star is distorted into an egg-like shape by the enormous gravitational field of the compact object. The material first spirals inwards in an accretion disk, getting hotter and hotter as it falls towards the compact object (just as water at the bottom of a waterfall is a tiny amount warmer than at the top). Towards the centre of the accretion disk, the material becomes so hot that it emits strongly in gamma-rays, the most energetic radiation in the electromagnetic spectrum

binary systems and the companion star is close enough to transfer material onto the neutron star, they are known as 'accreting X-ray pulsars' (Fig. 3). As this material falls onto the neutron star it becomes extremely hot and emits large numbers of X- and gamma-rays. These binaries can therefore provide a natural laboratory in which to study the interaction of ultra-hot material with ultra-strong magnetic fields. Such conditions are simply too extreme to be reproduced in laboratories on Earth. Integral will capture images of the high-energy emission from these objects with unprecedented detail, allowing astronomers a clearer look than ever before.

However, neutron stars are not the most bizarre objects that Integral will observe. Neutron stars containing more than about three times the Sun's mass become unstable and collapse even further, becoming a 'black hole'. These are perhaps the strangest objects in the Universe because nothing, not even light, can escape from inside the black hole. So the presence of a black hole can only be inferred by its effect on the surrounding objects.

Understanding black holes

Understanding the nature and properties of black holes is one of the key scientific objectives of Integral. The masses of black holes are thought to range from a few times that of the Sun to many millions of times that of the Sun. Scientists believe that such giant black holes lie at the centre of many galaxies, including our own Milky Way. When there is material close enough to be drawn into the hole by the enormous gravitational field, it will emit phenomenal amounts of energy before disappearing into the black hole. Such systems are known as 'Active Galactic Nuclei', or AGN (Figs. 4 and 5). We believe that there is a million-solar-mass black hole present in the heart of our Galaxy. It is not currently active, although it may have been in the past.

Figure 4. Artist's impression of a giant black hole, called MCG-6-30-15, located at the centre of a spiral galaxy similar to our own, but one hundred million light years away (courtesy of NASA/ Dana Berry)

However, from radio and optical observations it is known that the heart of our Galaxy is still a site of violent activity, perhaps resulting from past activity. At gamma-ray energies, this behaviour is brought clearly into view. Arching up from the centre of the Galaxy is an enormous cloud of anti-matter that is glowing brightly in gamma-rays, created by the annihilation of matter and anti-matter (Fig. 6). Integral will investigate the nature of this

Figure 5. Integral observing a galaxy that contains a massive black hole at its centre. From the region near the black hole two narrow jets are emitted. Integral will study the unknown mechanism responsible for jet production around massive black holes and also in the smaller black holes closer by in our own Galaxy

emission with unprecedented sensitivity and so help us to understand the nature of the giant black hole at the centre of our Galaxy.

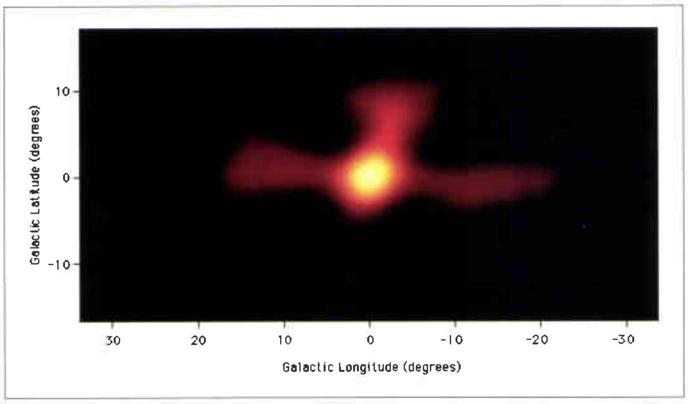

Figure 6. The very centre of our Galaxy is a violent place, as shown in this Compton Gamma-ray Observatory image. The nucleus is the bright spot at the centre, the horizontal structure lies along the Galactic Plane, and the mysterious 'anti-matter' cloud is located above the nucleus (courtesy of D.D. Dixon, Univ. of California Riverside, and W.R. Purcell, Northwestern University)

Integral will study yet another class of black holes. These are black-hole systems with masses just a few times that of the Sun. If these black holes are in binary systems, then the companion star can provide material that falls into the black hole. As this happens, the material gets extremely hot and emits X- and gamma-rays. Thus, the presence of intense X- and gamma-ray emission from a binary system may indicate the presence of a black hole, hidden from direct view. Many of these systems are 'transients', meaning that they do not give off gamma-rays most of the time and usually remain hidden amongst the billions of stars in our Galaxy. The study of these transient outbursts is of prime scientific importance and most weeks Integral will devote time to a search for new transient sources. Whenever a new transient is discovered, the Integral scientists will alert the worldwide astronomical community so that observations with other facilities and satellites can be organised. Integral will be able to address many outstanding problems in black-hole research, such as whether there are distinctive spectral signatures that can be used to discriminate between black holes and their cousins, the super-dense neutron stars.

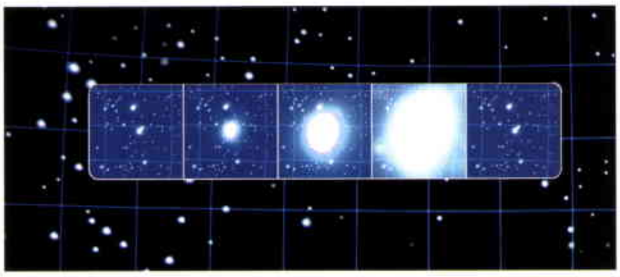

Figure 7. The sequence of five images is an artist's impression illustrating how a gamma-ray burst can flare dramatically over a short time interval, before disappearing never to be seen again. Gamma-ray bursts occur anywhere on the sky and it is impossible to predict when, or where, one will occur next

Probing the mysterious bursts

Around once a day, astronomical satellites detect sudden bursts of gamma-rays coming from anywhere in the Universe (Fig. 7). These bursts can be briefly the brightest objects in the gamma-ray sky, but are never seen to repeat. For many years, astronomers had no idea how far away these explosions were. This changed in 1997 when the Italian-Dutch satellite BeppoSAX provided accurate burst positions quickly enough to allow the still glowing debris to be detected in optical, radio and X-ray telescopes (Fig. 8). These observations showed that gamma-ray bursts occur at huge distances, similar to those of the farthest galaxies, and therefore that they are incredibly energetic, briefly glowing brighter than a billion stars.

Astronomers believe that this colossal amount of energy could be released when a massive star catastrophically collapses in on itself leaving a black hole, in a massive explosion known as a 'hypernova'. Not all gamma-ray bursts may have the same origin, and some astronomers believe that colliding neutron stars or black holes may be responsible for some of the bursts (Fig. 9). More observations of the glowing debris are desperately needed in order to understand what is really happening. However, now that BeppoSAX is no longer operating, it is much harder to find suitable gamma-ray bursts to investigate. The large fields of view of the Integral gamma-ray instruments will allow the chance detection of a few gamma-ray burst per month, a similar rate to that provided by BeppoSAX. In addition, Integral itself will be able to search the glowing debris for evidence of the atoms created.

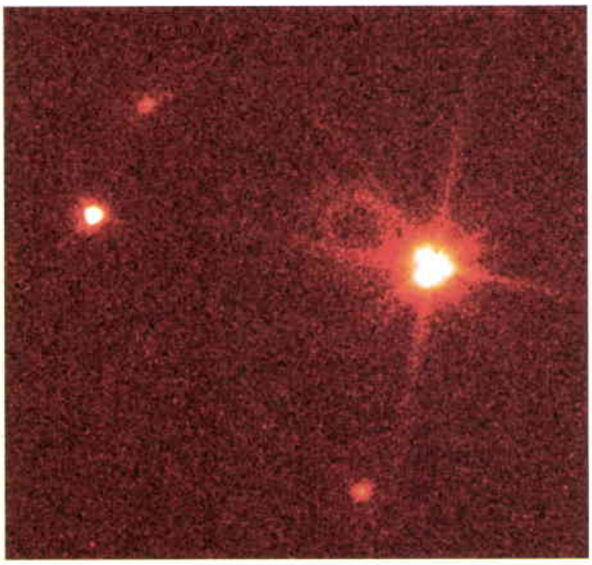

Figure 8. The optical counterpart of the gamma-ray burst of 1 March 2000. The RXTE, Ulysses and NEAR spacecraft all detected a 10 second burst of gamma radiation. Within 48 hours, astronomers detected a counterpart using optical, infrared, millimetre and radio telescopes. The Hubble Space Telescope captured this optical image and was the first to obtain an accurate distance to the explosion, placing it most of the way across the visible Universe. The Keck II telescope in Hawaii quickly confirmed and refined the distance measurement (courtesy of A. Fruchter, STScI)

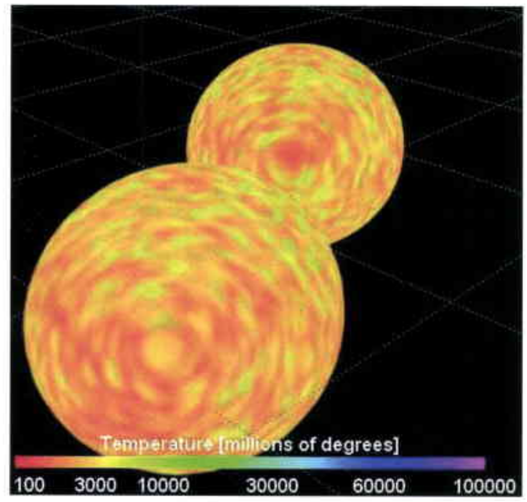

Figure 9. Scientists believe that colliding neutron stars, such as those depicted in this computer simulation by S. Rosswog (Univ. of Leicester) et al. may be a cause of gamma-ray bursts – the most powerful explosions in the Universe. As the neutron stars merge, they tear each other apart, briefly forming an accretion disk and jets before turning into a black hole. Some astronomers now believe that heavy elements, such as the gold in your jewelry, are most easily made in rare neutron-rich explosions such as these collisions. It is a strange thought that you may be wearing a souvenir of one of the most powerful explosions in the Universe!

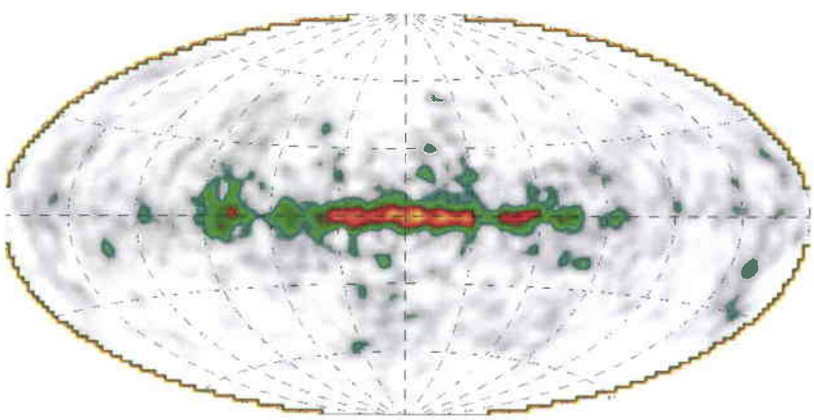

Figure 10. An all-sky map in the light of the 1.8 MeV gamma-ray line from the radioactive decay of aluminium. This map, displayed in galactic coordinates, combines data from nine years of observations by the COMPTEL instrument on the Compton Gamma-ray Observatory. The diffuse line emission is clearly concentrated in the Galactic Centre and along the Galactic Plane. Individual local enhancements, or 'hot spots', are also visible (courtesy of COMPTEL Collaboration and S. Plüschke, MPE)

Creating the atoms

Scientists are confident that most of the elements that we are made from were once in the hearts of stars. From there, they were released into space at the end of a star's life, often in a violent explosion called a 'supernova'. The precise nature of how this happens remains elusive and is one of the top goals of Integral.

The abundances of the elements can be measured directly on Earth and in meteorites. In addition, astronomical observations can reveal the composition of stars, galaxies, and the interstellar medium. Scientists believe that the very early Universe consisted almost entirely of hydrogen and helium, the simplest elements. All of the other elements were created inside stars or in supernova explosions. Most stars, including the Sun, generate energy by changing hydrogen into helium. When all of the hydrogen is burnt, helium can itself becomes the fuel. Most stars stop there, puffing off their outer layers into space, so that the enriched gas can become the raw material for the next generation of stars and planets. The remaining core of the star gradually cools becoming a 'White Dwarf' star, about the size of the Earth.

Not all stars continue shining faintly into a ripe old age. The most massive stars have very short lifetimes that may end in a massive supernova explosion. When such a massive star is blown apart, it may distribute elements such as carbon, oxygen, nitrogen, silicon, and sulphur into space. Heavier elements such as nickel can be formed during the supernova explosion itself and scattered into interstellar space. During the explosion, large numbers of gamma-rays are produced and as these pass through the cosmic debris, the newly created elements can be studied by their effect on the gamma-rays. Integral observations of these gamma-rays will provide the most direct method yet of studying the formation of the elements.

The COMPTEL instrument onboard NASA's Compton Gamma-Ray Observatory has for the first time produced an all-sky map in the light of the 1.8 MeV gamma-ray line produced during the radioactive decay of aluminium (Fig.10). This diffuse glow – possibly from the remnants of many galactic supernovae or novae explosions, or the result of stellar winds from very massive, young and hot stars – shows the clear presence of the Galactic Centre and the Galactic Plane. Integral will investigate the broad-scale distribution of this diffuse radiation with unprecedented sensitivity, energy resolution and imaging. Various 'hot spots' in the map could move at various relative velocities – measurable via slight shifts in the energy of the line due to the Doppler effect, and indicating the influence of galactic rotation.

The Integral Science Ground Segment

The Integral ground segment consists of two major elements, the Operations Ground Segment (OGS), described elsewhere in this Bulletin, and the Science Ground Segment (SGS). The SGS itself consists of two components, the Integral Science Operations Centre (ISOC), which is provided by ESA, and the Integral Science Data Centre (ISDC), which is nationally funded in the same way as the Integral instruments. The main interfaces and information flows are shown schematically in Figure 11. The ISOC, located at ESTEC, issues the Announcements of Opportunity (AOs) for observing time and handles the incoming proposals.

All proposals for observing time on Integral by the scientific community are assessed by an independent Time Allocation Committee (TAC). The accepted proposals are then processed at the ISOC into an optimised observing plan, consisting of a timeline of target positions, together with the corresponding instrument configurations. As part of this optimisation, the ISOC checks for targets close together in the sky which can be observed in a single pointing – so saving observing time. This is particularly important for Integral, where the observations are generally long and the fields of view of the gamma-ray instruments are very large. Optimised observing plans are then forwarded to the Mission Operations Centre at ESOC for the creation of the corresponding commands to be sent to the spacecraft.

observing programme, which will be forwarded to the Missions Operations Centre as before. The revised observing plan will be then made available on the World Wide Web so that astronomers who are planning coordinated observations will know the exact time that Integral will be observing. In order to support Integral users who have questions about any there is a Web-based Help Desk provided, jointly operated by the ISOC and ISDC.

The ISDC, located at Versoix in Switzerland, will receive raw science telemetry together with relevant ancillary spacecraft data from 0the OGS. These science data will be processed, taking into account the instrument characteristics, and raw data will be converted into physical units. Using the incoming science

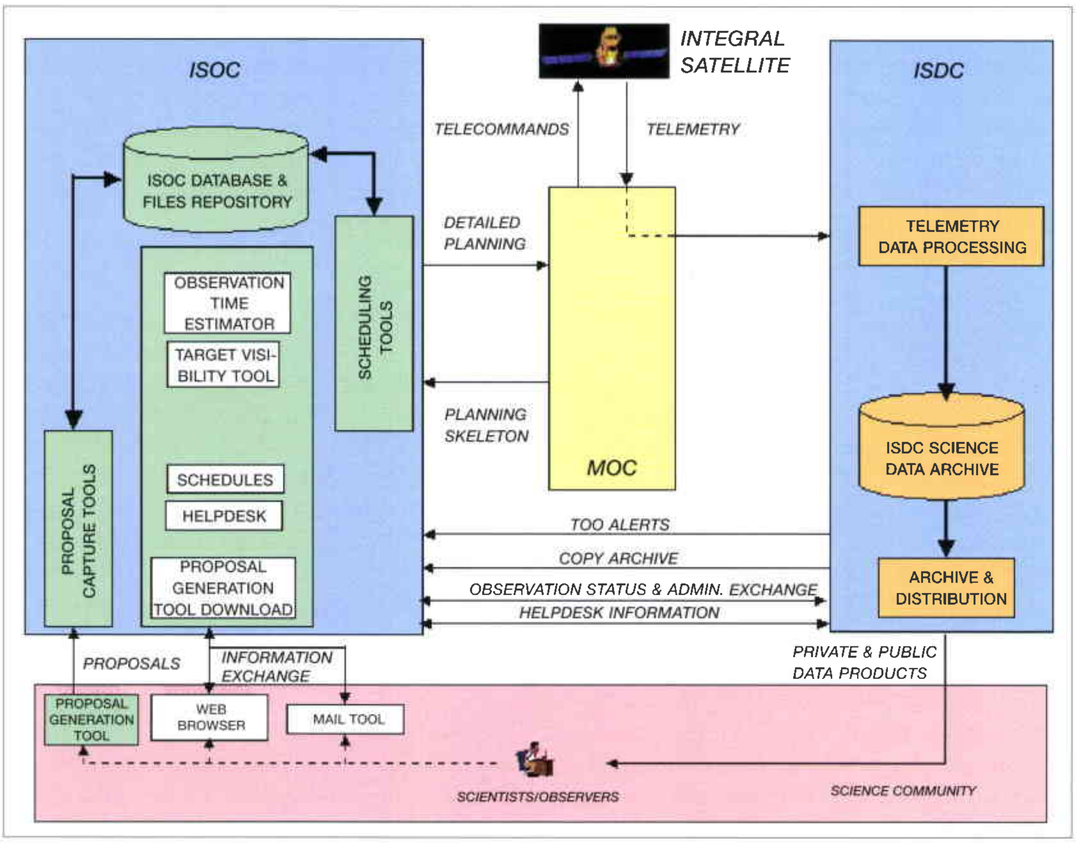

Figure 11. The blue boxes show the two parts of the Integral Science Ground Segment – the ISOC and ISDC – together with the main interfaces and information flows to the Mission Operations Centre (MOC), the scientific community and the Integral satellite

As discussed above, the gamma-ray sky is very variable, and interesting new targets may unexpectedly appear anywhere in the sky. These targets may be discovered using Integral itself, or by other satellites or ground-based observatories. When this happens, the astronomers who made the discovery may request a Target of Opportunity (TOO) observation with Integral. This is a request to interrupt the already planned sequence of Integral observations within 20 to 36 hours and observe the newly discovered target due to its high scientific priority. The Project Scientist will decide on the basis of scientific merit whether to proceed with the TOO request. If the request is granted, the ISOC will generate a new

and housekeeping information, the ISDC will routinely monitor the instrument science performance and conduct a quick-look science analysis in order to search for unusual and interesting events. Many of the TOOs expected during the life of Integral are likely to be detected at the ISDC in this way. As well as keeping an eye on the long-term health of the instruments, the ISDC will distribute science data products such as images and spectra for all four Integral instruments. These will be obtained using standard software-analysis tools developed by the ISDC and the instrument teams. By using these products astronomers who are not experts on the Integral instruments will be able to analyse

Integral data. Another very important role for the ISDC is to produce the Integral science archive for use by the astronomical community. A copy of this archive will be maintained at the ISOC.

The Integral observing programme
Integral is an observatory-type mission with a nominal lifetime of 2 years with an extension of up to 5 years technically possible. Most of the observing time (65% during the first year and 70% in year 2) will be awarded competitively to the members of the scientific community. The remaining fraction of time (i.e. 35% in year 1) is reserved for the Integral Science Working Team (ISWT) for its contribution to the mission. The main task of the ISWT is to monitor and advise ESA on all aspects of the Integral mission that affect its scientific performance. The ISWT consists of the instrument and ISDC Principal Investigators, representatives of the Russian and the US communities and the Mission Scientists who are independent of the instrument teams. In the first year, this 'guaranteed time' will be devoted to: (i) a Galactic Plane survey, (ii) a deep exposure of the central radian of the Galaxy, and (iii) pointed observations of selected regions and sources and TOO follow-up observations. In accordance, with ESA's policy on data rights, all scientific data will be made available to the scientific community one year after they have been released to the observer. Due to the intrinsically faint source intensities and comparably high background radiation, typical observations will last between about one day and three weeks and observers will receive data from all the simultaneously operating instruments onboard Integral.

The Integral open time observing programme for the first year has already been selected by the TAC, which was chaired by Prof. E.P.J. van den Heuvel of Amsterdam University. Observing time on a satellite is a very precious resource and Integral will only be able to carry out the very best of the 291 proposals received when ESA asked for ideas for the first year's observing programme. Indeed, astronomers asked for more than 19 times the open observing time available on Integral for the first year of operations. This remarkable oversubscription is testament to the scientific capabilities of the mission and the interest of the astronomical community in the topics that Integral addresses.

The open time programme provides for a wide variety of innovative studies of objects and phenomena never before accessible with such a powerful mission. About 40% of the observing time will be devoted to observations of compact objects such as stellar-mass black holes and neutron stars, 30% to the study of extragalactic objects such as AGN, and about 25% to the study of the formation of the elements. The TAC selected about twice as many observations as can be performed by Integral in the first year. This is to allow the ISOC some flexibility in planning which target is to be observed when, in order to minimise the time spent manoeuvring between targets. This planning has to take into account that some observations must be performed at certain times. This normally occurs when an observer needs simultaneous observations with other (ground or space-based) observatories, or because the object being studied may be variable and the proposed investigation can only be conducted at certain times (e.g. an observer may wish to study the eclipses of a binary star). In addition, Integral cannot point at any part on the sky at any time. This is because the solar arrays, which provide Integral's power, need to be pointed towards the Sun. The best proposals that are unlucky enough not to be scheduled in the first year will automatically be carried over to the next year.

Conclusions
With ESA's XMM-Newton X-ray observatory producing a wealth of new scientific results, astronomers from all over the world are eagerly awaiting the views of the even higher energy gamma-ray Universe that Integral will provide. The improved imaging and spectral capabilities of Integral compared with previous missions, as well as the simultaneous X-ray and optical monitoring, will provide the scientific community with an unprecedented opportunity to investigate the nature of the extreme Universe in the next years.

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ISS Cooperation: Recent Developments in Rule-Making

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Until the adoption of the Code of Conduct for the ISS crew on 15 September 2000 by the Multilateral Coordination Board (MCB), the rule-making process for all aspects of the cooperation was based on high-level international negotiations between the Partner States or Partners, on the one hand, and the Cooperating Agencies, on the other, the latter also being referred to as 'the Partners'. These negotiations have produced legal instruments which have been published and also posted on the Internet, and can therefore be consulted by anyone who is interested. Recent developments have shown that responsibility for rule-making on ISS cooperation is shifting from the relatively self-contained environment of international negotiations to a broader base that is more difficult to control.

The recent changes

Since preparations for utilisation of the International Space Station (ISS) are now fully under way, the cooperation's management bodies established pursuant to the Memoranda of Understanding (MOUs) linking NASA and each of the other Cooperating Agencies, have started to take decisions and develop detailed rules that affect the rights and interests of all players in the cooperation, including users and the Agencies, thus becoming the forums for developing far-reaching rules.

These recent developments have a number of practical consequences. Firstly, the Agencies' representatives on the various bodies directly engaged in the rule-making process are now more numerous and they are meeting more often than during the IGA (International Governmental Agreement) and MOU negotiations, not to mention frequent changes in personnel assigned to these tasks. There is therefore a strong possibility that the scope of the original ISS rules will be somewhat broadened over time, because of the multiplicity of interpretations and applications.

Secondly, there is no systematic exercise under way within the partnership to decide on consistency between the rules being developed in the various cooperation bodies, compared not only with one another but also with the original prescriptions of the IGA and MOUs. It has to be realised that some rules developed in the Operations Panel and User Operations Panel (SOP/UOP) may also be taken up in a different form in the Multilateral Crew Operations Panel (MCOP), for example, because there will obviously be some level of interaction between the handling of payloads and astronaut activities.

Thirdly, no principles or organisation have yet been agreed for ensuring systematic and formal notification of the detailed rules being developed by all the cooperation bodies, not only among the Partners, but also internally to the different services concerned in the Cooperating Agencies. Notification of new rules within the partnership, to ensure transparency in their application among other things, is obviously imperative because the rights and interests of third parties, essentially the users, will be affected on a daily basis by these new rules, through the contractual relationships to be established between the Agencies and users.

Fourthly, the inadequate level of publicity for new rules outside the partnership may make it difficult for scholars to carry out research using original material on any given subject, which often might have implications far beyond ISS cooperation. In fact, there will probably not be a complete lack of external publicity about new rules, but rather a lack of consistency in practice since the Cooperating Agencies have a wide variety of policies and practices in this regard, and also because the legal regime governing public access to information differs from one Partner State to another.

The Cooperating Agencies have discussed the possibility of giving in the future a legally-binding status, with appropriate formal publicity, to a number of texts developed through dedicated Partners' task forces or ISS management bodies, when such texts affect the rights and obligations of the ISS Partners or individuals. As the expression 'implementing arrangement' is not defined strictly in the IGA, this could provide the possibility to include all 'legally-binding' texts in a new category of ISS implementing arrangements. Until now, only bilateral barter arrangements have been characterised as 'implementing arrangements' and concluded in a more formal manner. However, because of internal requirements making it somewhat difficult for a number of Cooperating Agencies to conclude a legally-binding document on their own, they have decided that a number of documents, such as almost all of those described below, will be applicable merely as a 'process' or as 'guidelines' complementing obligations contained in the IGA and MOUs. This refers to documents laying down a course of action to be put into operation straightforwardly by the Cooperating Agencies, without necessarily generating rights and obligations in international law.

Arrangement on life-sciences flight experiments on board the ISS

We are currently seeing significant interest from existing space groups working in various fields of research in organising their ISS utilisation. The question of whether utilisation of the Station is already fully covered by the Space Station Intergovernmental Agreement (IGA) and the MOUs has been asked on numerous occasions by potential ISS users. It is clear that both the IGA and the MOUs contain a number of overarching rules outlining how ISS utilisation rights will be apportioned, and otherwise organised and controlled, between the Partners. It is also clear that whenever a Partner decides to share its own utilisation rights in a cooperative framework with other Partners under the IGA and MOUs, the actual cooperation contemplated for such utilisation will be over and above its existing obligations under the IGA and MOUs, and will therefore entail new commitments, and thus new arrangements.

The International Space Life Sciences Working Group (ISLSWG) is promoting the adoption by the partners of a framework arrangement that will outline the basic rules, including the respective parties' responsibilities, for conducting life-sciences experiments on board the ISS. The ISLSWG is a body established a number of years ago to conduct research in that field onboard the US Space Shuttle and is composed of representatives not only from the ISS Cooperating Agencies, but also from European national space agencies such as CNES and DLR. The understanding is that such a framework arrangement would serve as an 'umbrella' for a series of letter arrangements (i.e. additional arrangements in a simplified format), each to be concluded over the years and spelling out more precisely the details of specific experiments.

Under the draft arrangement finalised in recent weeks, four of the five ISS Cooperating Agencies (the Russian Space Agency having chosen not to join the others in this exercise), as Parties to this arrangement, have agreed to:

- use consistently the ISLSWG-defined process for the advertisement of opportunities, review

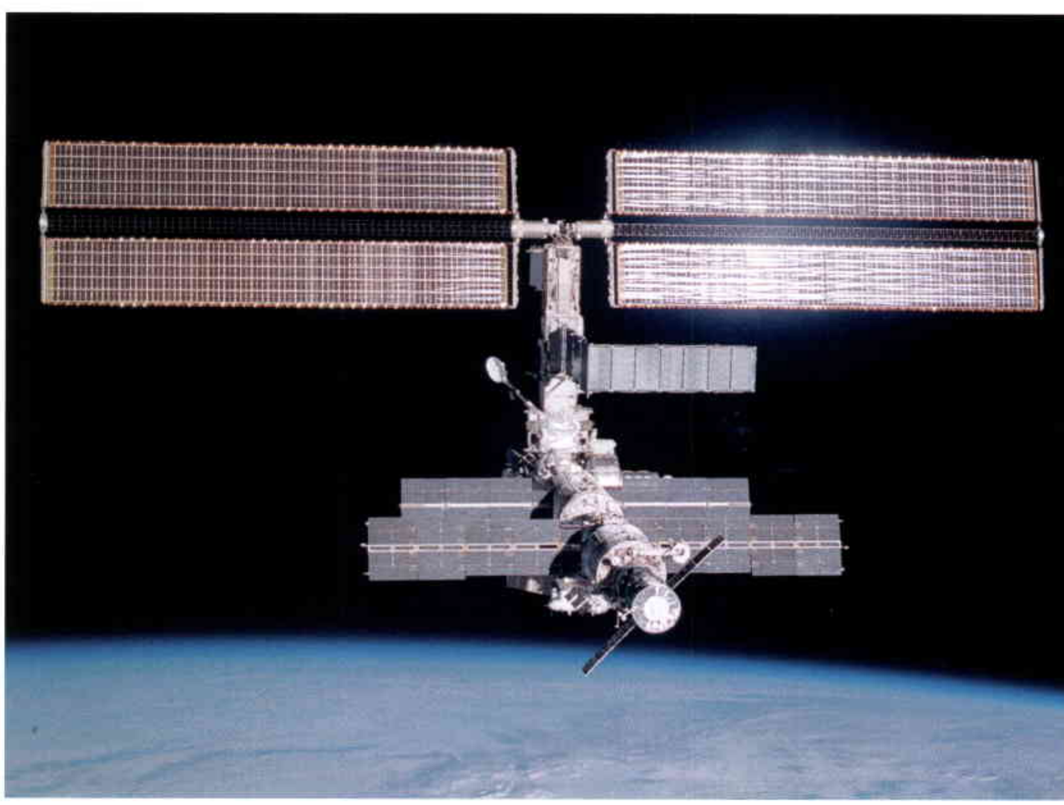

Figure 1. The in-orbit configuration of the International Space Station in December 2001

Figure 2. ESA Astronaut Claudie Haigneré at work on the ISS in October 2001

of proposals and selection of life-sciences experiments
- make available to the international life-sciences research community their life-sciences hardware and utilisation resources
- share the cost of common activities conducted for the purpose of executing the international life-sciences research programme, such as the administration of the peer-review process.

Obviously, this approach could be used for other fields of ISS utilisation in the future.

Guidelines on commercial activities pertaining to the ISS

Since December 2001, the ISS Cooperating Agencies have held discussions on several occasions to develop a text for guidelines applicable to commercial activities pursued within the framework of the ISS programme. These activities could be defined as: (a) the use of all elements of the ISS, including provision of flight opportunities to space tourists, and (b) a number of activities conducted on Earth for exploiting the overall image of the ISS, such as advertising, merchandising and sponsorship, for the purpose of collecting revenue that could then be spent on ISS utilisation.

From the reading of the draft guidelines finalised by the Multilateral Commercial Group (MCG) in March 2001, one can conclude that the drafters have been remarkably prudent. They have recognised, to all intents and purposes, that commercial activities in the various fields shall be 'promoted and encouraged' and that existing rules, i.e. in the IGA, the MOUs and the Crew Code of Conduct, shall be applied whenever relevant to ISS commercial activities. This prudence could be explained by two factors: (a) the fact that utilisation of the ISS is considered under the IGA as a right that could be freely exercised, and hence the reluctance to accept new impediments, and (b) the significant difference existing between the Partners' markets for both conventional (utilisation-related) and non-conventional (i.e. image-related) ISS commercial activities and therefore the need to not jeopardise the future prospects for extra revenues.

The positive side of the exercise having resulted in these guidelines is that the Partners have put on paper their basic understandings of the way in which ISS commercial activities should be carried out, thus providing a first version of a document that could gradually be expanded and improved. This is particularly important with regard to the non-conventional activities for which the Cooperating Agencies have accepted: (a) to develop a ISS global brand management plan, preferably before the end of 2002, and (b) to limit themselves to the promotion of their own contributions to the ISS, and therefore not use the global ISS image in their commercial promotion activities before the completion of the above-mentioned plan.

Process for the involvement of non-Partner entities in the ISS Programme

The Cooperating Agencies worked throughout 2001 to develop a process, finally approved in March 2002 by the MCB, for implementing Articles 6.4 and 9.3(a) of the IGA pertaining to non-Partner participation in ISS cooperation. The main objective of these provisions is to provide all Partner States with the occasion to assess the requests, primarily from a 'foreign-policy standpoint', for participation in ISS activities of States, or agencies or private entities or individuals of States, other than those having signed the IGA. It is understood that all other technical and programmatic aspects, such as safety implications, should generally be handled through the ISS management bodies in due time.

One of the time-consuming issues was to determine whether a strict interpretation of the IGA would make it necessary to request all Partners' concurrence or consensus only when contemplating 'the use of a user element' (i.e. laboratory) by a non-Partner. Finally, the Cooperating Agencies agreed on a broad interpretation of the IGA which would make it necessary to request consensus or concurrence by all Partners regarding use of any element, whether a user resource or another element of the ISS, by a non-Partner, including the presence of a non-Partner's spaceflight participant onboard the ISS. They also agreed that there was a need to provide for a time-limited ad-hoc process, i.e. with strict specific delays for all Partner States to provide an answer, because of: (a) the burden and extra costs involved, and the corresponding contractual uncertainties, for the sponsoring Cooperating Agency, and (b) the hope that the processing of consensus/concurrence requests should become a fairly routine matter over the years, and such processing should therefore be both simple and transparent.

Criteria for the selection of ISS crew members

In response to the difficulties encountered by the partnership during preparations for the flight of the first space tourist using the Russian Soyuz vehicle, the American Dennis Tito, the Cooperating Agencies' representatives meeting at the MCOP have developed a document entitled: 'Principles regarding processes and criteria for selection, assignment, training and certification of ISS crew members', which became effective in November 2001. This document addresses such matters as suitability criteria, including medical, behavioural and linguistic aspects, the process for the assignment of crew members to a specific flight, the requirements for training and the certification of flight-readiness.

It is worth mentioning that, for the first time, a document developed multilaterally establishes two categories of astronauts, the professional astronaut and the spaceflight participant, the latter being an individual assigned for a single mission under a short-term contract concluded with the sponsoring agency providing the flight opportunity. The document indicates that both categories of astronauts could be considered for an Expedition Crew flight opportunity, i.e. those long-term flights accruing to the Partners by virtue of their participation in the cooperation pursuant to the IGA and MOUs, or a visiting crew flight opportunity, this being a short-duration mission including a sojourn onboard the ISS. Clarification of the selection criteria among the Partners through the drawing up of the above document contributed significantly to the success of the flight of the second space tourist, the South African Mark Shuttleworth, in April/May 2002.

Conclusions

The interests of the ISS users, whatever their fields of activity, are likely to be at the heart of the rule-making process for ISS cooperation for the foreseeable future. The main challenge for the ISS Partners is to streamline and publicise the various sets of rules – those already existing and those still being developed – in such a way as to make them transparent and easily understandable to all concerned. Also, there will be a significant benefit in ensuring over time the legally binding character of the various rules, within the meaning of that expression in the ISS partnership. This will contribute to the establishment of greater legal certainty when proposing to potential users a series of prescriptions developed by the Partners which are bound to affect the rights and interests of those users.

Visiting the ISS – by Taxi

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Yes, it is possible to visit the International Space Station (ISS) by taking a taxi, if the 'taxi' is a full Soyuz spacecraft and the training qualifies you for the flight. The third ISS Taxi mission flew in April/May 2002 and, as with the second Taxi mission in October 2001, a European astronaut was again onboard.

Introduction

The primary goal of the Taxi missions is to replace the Soyuz lifeboat attached to the ISS before its 6-month warranty expires. A fresh Soyuz is delivered by a crew of three, who stay aboard the ISS for about a week and work alongside the resident Expedition crew, before returning to Earth in the 'old' Soyuz.

Figure 1. Yuri Gidzenko (foreground) and Roberto Vittori training in the Soyuz simulator at Star City

In mid-2001, the Italian space agency, ASI, and ESA negotiated a contract with the Russians to use one of the Soyuz seats for an Italian astronaut within the framework of the ESA/ Russian agreement on cooperation in manned spaceflight. ESA astronaut Roberto Vittori trained as the Soyuz flight engineer and was launched on 25 April 2002 aboard Soyuz-TM34 from the Baikonur Cosmodrome, together with Commander Yuri Gidzenko and Spaceflight Participant Mark Shuttleworth. Docking with the ISS after 2 days, he spent 8 days onboard. On 5 May, the crew returned safely in Soyuz-TM33, in which ESA astronaut Claudie Haigneré had reached the Station more than 6 months earlier.

Training

Roberto's background as a distinguished test pilot in the Italian air force and his 3 years of Shuttle Mission Specialist training at the NASA Johnson Space Center in Houston were excellent preparation for the mission. He began training in August 2001 at the Gagarin Cosmonaut Training Centre at Zvezdny Gorodok ('Star City'), near Moscow. Training was initially alongside ESA astronaut Frank De Winne, who was preparing for his October 2002 Taxi flight. The first lessons were with the assistance of an interpreter, which made the 3.5 m^3 of the Soyuz interior very cramped indeed during practical work. Eventually, of course, Russian-language courses meant that both ESA cosmonauts could dispense with the interpreter's services.

The Russians have extensive experience in training crews for spaceflights so, even on such a tight schedule, they delivered the required courses for Roberto. His role was that of Flight Engineer, sitting to the left of the Commander, and in charge of the flight computer, the engines and the propellant system, among others. He supported the Commander in all the flight phases, including the ascent, the orbital manoeuvres, the approach and docking to the ISS, and finally the undocking and return in the swapped Soyuz. The Flight Engineer has to

Figure 2. Launch of Soyuz-TM34 from Baikonur Cosmodrome, on 25 April. This mission departed from the same pad as Yuri Gagarin

handle several life-support system elements, planning and controlling the careful exploitation of the limited Soyuz resources.

Commander Gidzenko was already well-known to ESA from the highly successful and harmonious EuroMir mission in 1995, when he spent half a year aboard Mir with ESA astronaut Thomas Reiter. Yuri and Roberto were accompanied by Mark Shuttleworth, a South African citizen, who flew on the basis of a commercial contract with the Russian Space Agency and partner organisations. After the tourist flight in 2001 of Dennis Tito, the ISS Partners agreed on a set of rules for non-professional astronauts. A minimum of training and safety rules was defined, together with health requirements to avoid endangering the rest of the crews.

Days 1 & 2
Today, the crew settled into a flight routine aboard Soyuz-TM34, reporting every 90 minutes to the Moscow Flight Control Centre. A small orbital correction during the 17th orbit went according to plan to catch up even faster with the Space Station. Life on Soyuz between communication passes and manoeuvres is quite spartan: no hot drinks or food, just canned food, a sip of tepid water and some fruit juice in tubes. But, as a transport vehicle, it fulfils its role perfectly.

The experimental programme

Though the amount of European research hardware aboard the Station is growing, the time for training and collecting life-sciences baseline data is a bottleneck for performing the experiments. So the set of experiments taken by Roberto Vittori into space on his 'Marco

Day 3
Finally, after 2 days in the cramped 10 m³ cabin, the large Station appeared in the periscope in front of Yuri in his centre seat and on the small video screen. The docking went perfectly - completely automatic and on time. Hatch opening and a warm welcome by the ISS Expedition crew was certainly unforgettable. From TsUP, the ESA Director of MSM, Jörg Feustel-Büechl, talked with Roberto and the Expedition-4 Commander, Yuri Onufrienko, during the first teleconference shortly after docking.

Figure 3. Roberto Vittori floats through from Soyuz into the Station

Polo' mission reflected the very short lead time. For example, there was no time to train him in the use of the large units like the Human Research Facility, installed in the US Destiny laboratory. So the set had to be limited to three life-science experiments through ASI, a number of ground experiments and – a first for ESA – a commercial venture called BMI, a blood measuring instrument. Intospace of Hannover (D) acted as ESA's agent for this commercial undertaking.

Russian specialists were contracted to develop the procedures and to support the experiments. ASI and ESA staff provided the necessary inputs and followed the progress during the flight in close cooperation with their Russian counterparts.

Figure 4. The Taxi crew in the ISS Zvezda module. From left: Yuri Gidzenko, Roberto Vittori and Mark Shuttleworth. (NASA)

Day 5
During his fifth day in space, Roberto continued working on his experiments. The ALTEINO measurement complex needed special attention, with two sessions using the electroencephalogram to record his brain's electrical activity. Roberto also started a second 48 h run for the radiation spectrometer.

Yuri Gidzenko was busy on the ground link with the Plasma Kristall Experiment, a Russian-German-French experiment to investigate transient filigree features of dust particles in a gas environment, visible only in microgravity.

A pass over Italy again gave Roberto an opportunity for photographic coverage. These images were downlinked. The crew reported no major problems with the Station's systems. Working with six people aboard needs increased crew activity coordination and voice/video downlinks. Communication times for Roberto's experiments are handled with great generosity.

Life aboard the Station

With the arrival of a Taxi crew at the ISS, public interest focuses for a few days on this outpost in space. It should not be forgotten that, since November 2000, the Station has been continuously inhabited and the assembly work has been in full swing. So, even for Yuri Gidzenko, part of the first ISS expedition crew, life onboard was very different from his experiences of November 2000 – March 2001. Destiny, the US laboratory module, has enlarged the volume of the Station and its operational capabilities, the Canadian robot arm has become active, and new communication and data downlinks have been added.

For each Taxi crew and, even more so, each Expedition crew, the training programme has to be highly individual. Though crew interaction is essential for the success of the activities squeezed into the 8 days aboard the Station, the crews hardly have time to get to know each other on the ground beforehand and therefore have to improvise to a certain extent when meeting onboard. The activities of a Taxi crew are mostly orchestrated by the Moscow control centre, TsUP, in close coordination with the Station lead mission control centre in Houston, MCC-H. The activities are then finalised and integrated into a daily activity plan for both crews, called 'Form 24'. Details of the activities and updates to the procedures for the next day are linked up as 10-15 radiograms every day. The crew convenes in the evening and goes through the next day's activities, before reiterating the plans in the Daily Planning Conference. Roberto by contract counted as a Russian crewmember and therefore worked under the authority of the onboard Commanders and the Moscow flight directors.

Life in the Control Centre

The interaction of the ESA/ASI support group with Roberto followed the lines described above for planning and communication with the whole ISS crew. The main means of interaction were the two Daily Planning Conferences, when all responsible centres on both sides of the Atlantic joined in a space-to-ground teleconference to clarify changes to the preliminary planning. Whenever the crew called down throughout the day with specific problems or questions, the calls were monitored and answered as quickly as possible by voice call or in a radiogram. When time allowed, written information was given in both official ISS languages: English and Russian.

Day 6
Roberto started his sixth day in space with a televised connection to Brussels, when he talked with European Commission President Romano Prodi and ESA Director General Antonio Rodotà. Then Roberto gave a tour of the Soyuz spacecraft to children watching in Rome. After his well-earned breakfast, Roberto pressed on with the day's experimental programme, focusing on the VEST test of new clothing materials and the CHIRO handgrip experiment.

Figure 5. Roberto Vittori testing communication equipment aboard the ISS

The Russian experts in TsUP freely included their operational colleagues from ESA's Astronaut Centre in their daily work, reviving the friendly experience of the many flights with European astronauts on Russian spacecraft.

With Taxi crews, exchanges are made during communication passes over Russian territory, when the Station is in line-of-sight of Russian ground stations, using VHF channels. Matching crew awake and work time (following GMT) and the actual orbital times of these passes meant that only three or four useful passes per day remained for information exchange or even TV downlinks. Here, a new characteristic of today's Taxi flights became evident: the presence of a paying customer with a strong interest in publicising his stay aboard the Station with the help of video coverage. By far most of the longer VHF passes with video connection were used by Mark Shuttleworth for broadcasts from space. Being blocked by TV events, these passes could not be used for reports on the experiments or system activities. ESA and ASI had the two remaining slots for TV events with the crew and Roberto.

Better checked twice

The main task of a Taxi crew is accomplished when the new Soyuz docks to the Station. Access to a rapid-return vehicle for the Expedition crew is then assured for another

Days 7 & 8
Roberto continued with his experiments and began preparing for his return: some 50 kg of payload was to return, including 15 kg of experiment results from the Italian/ESA science programme. On 2 May, South African Mark Shuttleworth received a call from ex-president Nelson Mandela. Delivering a message of admiration for the technical achievement evident in the ISS and of peaceful cooperation for the benefit of all, Mandela's voice not only came across the 400 km up to the Space Station, but also across all national and cultural barriers. Yuri and Roberto thanked Mandela for the words of support. Calling him by his honorary name 'Madiba' as the head of the family, Mark described how the work onboard ISS is helping to improve life on Earth.

One orbit later, Roberto exchanged similar views with Italy's President of the Chamber of Deputies, Signor Casini, and ASI president Sergio Vetrella. A problem with the data storage of the CHIRO computer unit finally gave the ESA/ASI operational group at TsUP something to work on. A solution was worked out and the procedure uplinked to ensure that all experiment data were returned to Earth. ESA astronauts Paolo Nespoli and Reinhold Ewald as Crew Interfaces relayed Roberto's information and requests during the voice calls. ASI mission managers Fabio Bracciaferri and Simona Di Pippo and science coordinator Maria Kristina Falvella represented the programme side in TsUP.

200+ days. Taking the 'old' Soyuz craft back to Earth allows items and experimental results to be returned, although the capacity of this small spacecraft is very limited. Finding safe storage places in containers located at almost unreachable places in the innards of the Soyuz capsule is a near-nightmare. This is still the part of the mission when, despite all the careful planning, the Soyuz Flight Engineer, working closely with the Commander, has to be creative. As a result, the 2 days before undocking are mostly freed of other activities for both of them so that they can focus on re-activating their return Soyuz after its long period of storage, checking it out and packing it with material requiring safe return. In addition, some Station rubbish is stored in the disposable Orbital Module, to burn up in the atmosphere on the way down. Every item stowed in the many tight locations is checked and double-checked to avoid expensive oversights.

The next Taxi

While the analysis of the experiment data that Roberto acquired during his flight is in full swing, the next ESA astronaut is preparing for lift-off. Frank De Winne will take the Flight Engineer position in the first uprated Soyuz-TMA spacecraft in October. The lead time for his training and the progress of deliveries to the Station will allow him to use the Microgravity Science Glovebox (MSG). This ESA-built facility was bartered with NASA and delivered to Destiny in June by the STS-111 mission. The demanding number and characteristics of the experiments mean that the flight's funding organisation, Belgium's Office of Scientific, Technical and Cultural Affairs (OSTC), has asked ESA's Directorate of Manned Spaceflight and Microgravity to set up an organisation for handling the experimental programme.

Communication links between the ISS Partners are improving all the time and more services of the Interconnected Ground Segment (IGS) for European participation in the Station are becoming available. This network will provide support and monitoring functions from ESTEC, EAC and the Belgian user centre for Frank while he is aboard the ISS.

As always, the Taxi, Shuttle and Expedition crews rely on the close and motivated cooperation of the international teams on the ground and in space for their success. esa

Days 9 & 10

Yuri and Roberto were busy packing all the equipment into the already crowded space of the return module, working late to get everything done. The ALTEINO radiation spectrometer (continuously registering charged particles since arrival) was the last experiment to be shut down. The hatches were closed at 21.30 UT on 4 May and undocking came at 00:28 UT early Sunday morning. The deorbit burn began on the first orbit over Kazakhstan, and landing came at 03.52 UT 5 May. With the help of helicopters and all-terrain vehicles, the rescue specialists (including ESA crew surgeon Filippo Ongaro) followed the parachute descent. They helped the cosmonauts out one by one. In a medical tent, the exhausted crewmembers changed into more comfortable clothing and medical monitoring showed they were fit for the return flight to Star City. A long journey with a happy ending

Figure 6. Roberto Vittori safely back on Earth on 5 May 2002

The Space Factor

– Fundamental and applied research benefiting Europe's citizens and economy

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Although 'made in space' products are not expected to appear in the near-future, space is gaining interest as an area for industrial or applied R&D. ESA is supporting a growing number of projects involving non-space industries and other third parties. This article gives an overview of the potential of research in space to develop valuable applications on Earth.

Introduction

Some 20 years ago, the title of this article might have carried an additional letter: *The Space Factory.* In those days, it was believed that the microgravity environment in space had such high potential for developing new technologies and products that complete industrial plants would soon appear in the skies.

Since then, of course, these expectations have dimmed considerably, the main reason being the low number of flight opportunities and the high costs and long waiting times associated with performing experiments in space. It should not be forgotten that early projections predicted up to 60 Space Shuttle launches per year!

Reality has lagged behind those early expectations by almost a full order of magnitude. Nevertheless, progress has been made and, although 'made in space' products are not expected to appear on the market anytime soon, space as an area for industrial or applied research and development is gaining interest.

ESA is at the forefront of this development and is supporting a growing number of projects in which non-space industries, hospitals and other third parties are participating. This article gives an overview of the potential of research in space to develop valuable applications on Earth.

Basic research

In the past two decades, research in life and physical sciences in space has matured. The number of publications in international, peer-reviewed journals has almost doubled, both in number and quality (as measured by the 'impact factor'), as can be seen from Figure 1. These findings are confirmed by more recent surveys at national level in several European countries. In the last few years, publications on space experiments have even surpassed the average impact factor of publications in the respective disciplines.

Experiments are selected by independent, international peer reviews according to the most stringent, internationally accepted procedures and criteria. Presently, the success rate for proposals is of the order of 30%, a figure that is generally accepted to be the optimum in science reviews, ensuring high competition and scientific quality without discouraging proposers until they lose interest in applying.

Indeed, it is interesting to note that this competitive environment and the resulting high quality of the selected experiments attract newcomers and scientists of high reputation rather than deter them. A survey on proposals submitted in response to recent Announcements of Opportunity (AOs) shows that a third of scientists are participating for the first time in a space experiment. Currently, the database of interested scientists and industrial users encompasses more than 12 000 individuals in Europe.

Since 1998, almost 800 proposals have been received, of which 256 have been rated as Outstanding or (Highly) Recommended by the peers. In total, more than 1100 scientists are participating in these proposals directly, and several hundreds more are involved indirectly. Figure 2 gives a distribution per country of the scientists involved in these projects. Several non-ESA member states are included in this list, notably the US, Russia and Japan, plus several East European countries (Hungary, Bulgaria, Czech Republic, Lithuania, Poland and Romania). This demonstrates the global character of the research community.

Applied research
In any scientific discipline, basic research is the starting point for progress. For that reason, basic research has received continuous support within life and physical sciences in space. Proposals of scientific excellence will generate new ideas in the pure sciences, that will, after gestation, find their way into novel practical applications.

A good example is the development of the laser. First predicted on theoretical grounds by Albert Einstein in 1917, the first real operational laser was not built until 1960. Nowadays, lasers are found in numerous appliances such as printers and CD players. From this perspective, it is surprising to see that several concrete ideas for applications are already emerging in life and physical sciences in space.

As instructed by the 1995 Ministerial Council, ESA has actively pursued applied research on the ISS. An important first step was the establishment of Topical Teams of scientists from academia and industrial R&D laboratories. These teams are promoting dialogue between the partners, identifying common interests and developing concrete suggestions for application-oriented research.

The second step consists of incorporating application-oriented research in ESA's AOs for Life and Physical Sciences. The first was issued in 1998. Important new elements were that the AOs:
- deal with basic and applied research,
- call for research programmes, rather than proposals for individual flight experiments,
- call for teams with a European dimension, rather than individual Principal Investigators,
- strongly welcome partners from non-space industries.

Since 1998, some 150 proposals for applied research have been received. As for basic research, these proposals have been reviewed by independent peers using basically the same criteria, but now including the element of 'application potential'. Again, the average success rate in this review ended up at about 30% – 43 projects have been approved (Table 1).

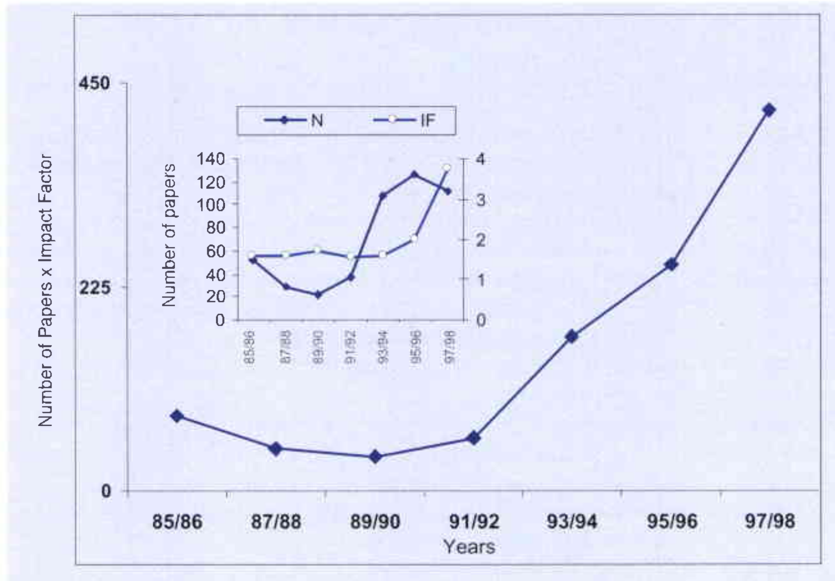


Figure 1. Increase in *quantity* and *quality* of publications in space-related European life sciences over the past few years. From a survey made in 1999

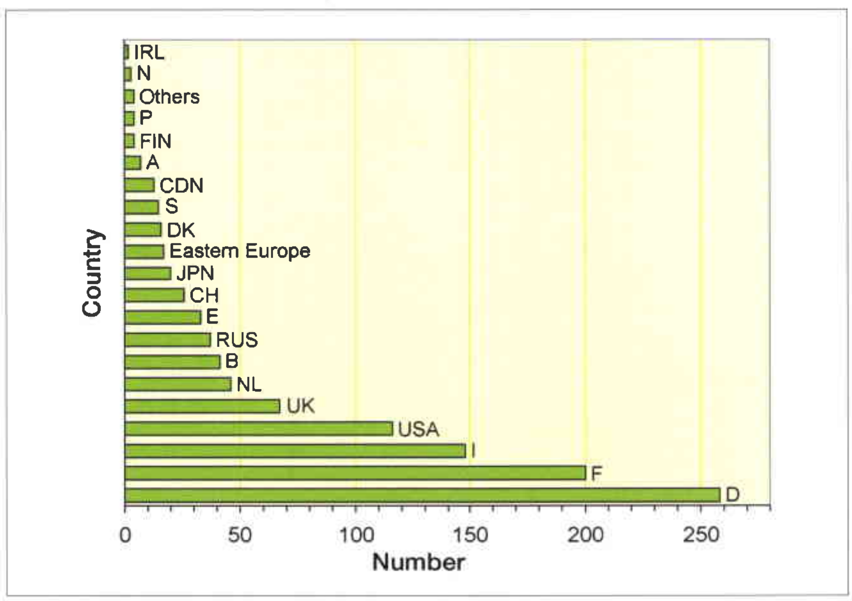


Figure 2. Distribution of the 1077 scientists involved in approved projects that form the scientific and industrial basis of ESA's life and physical sciences in space (ELIPS) programme

It is essential to recognise that all these 43 projects are run by trans-national teams. There is hardly any project in which participants from fewer than three European countries are involved. Also, as requested in the AO, the presence of researchers from industry is apparent. In total, 116 European companies are involved, among which there are some very large multinationals and a significant number of start-up companies and Small- and Medium-sized Enterprises.

As ESA does not fund the research activities of the industrial participants, they are committed to bring their own funding. Also, the funding for the non-industrial partners was limited. In particular, ESA provides funding to a fixed maximum amount determined by the application potential as determined by the peers. If there is no application potential, ESA's

Table 1. The 43 approved applied research projects.

AO Number	Name of Project	Discipline	Coordinator
AO-99-003	Modular space bioreactor for medically relevant organ-like structures	Biotechnology	Cogoli
AO-99-007	Investigations on soot concentration and primary particle sizes by advanced laser-induced incandescence.	Physical Sciences	Will
AO-99-010	Undercooling and demixing of Cu-Co alloys	Physical Sciences	Egry
AO-99-013	Vibration exercise as a countermeasure for muscular atrophy and bone loss	Life Sciences	Felsenberg
AO-99-021	Thermal transport phenomena in magnetic fluids under microgravity conditions	Physical Sciences	Odenbach
AO-99-022	Thermolab – high precision thermo-physical property data of liquid metals for modelling of industrial solidification processes	Physical Sciences	Fecht
AO-99-023	Non-equilibrium solidification, modelling for microstructure engineering of industrial alloys	Physical Sciences	Herlach
AO-99-026	Solidification morphologies of monotectic alloys	Physical Sciences	Ratke
AO-99-030	2d and 3d quantification of bone structure and its changes in microgravity condition by measures of complexity	Biotechnology	Gowin
AO-99-031	Microstructure formation in casting of technical alloys under diffusive and magnetically controlled convective conditions	Physical Sciences	G. Mueller
AO-99-035	Crystallisation of CdTe and related compound	Physical Sciences	Fiederle
AO-99-045	Study of an imposed electrostatic field on pool boiling heat transfer and fluids management	Physical Sciences	Grassi
AO-99-052	Fundamental and Applied Studies of Emulsion Stability (FASES)	Physical Sciences	Passerone
AO-99-058	Development and application of a miniaturised respiratory sensor system	Life Sciences	Fasoulas
AO-99-075	Development of advanced foams under microgravity	Physical Sciences	Banhart
AO-99-081	Long term microgravity: a model for investigating mechanisms of heart disease with new portable equipment	Life Sciences	Norsk
AO-99-083	Chemo hydrodynamic pattern formation at interfaces	Physical Sciences	Mueller
AO-99-085	Laminar diffusion flames representatives of fires in microgravity environment, combustion properties of materials for space applications	Physical Sciences	Joulain
AO-99-091	Eristo-osteoporosis	Biotechnology	Braak
MED-024	Eristo-osteoporosis (funding added to above contract)	Biotechnology	Braak
AO-99-094	Combustion properties of partially premixed spray systems in fields of droplet and spray combustion	Physical Sciences	Eigenbrod
AO-99-098	Perception of gravity, signal transduction and graviresponse in higher plants by innovative genomic technologies	Biotechnology	Palme
AO-99-101	Study and modelling of nucleation and phase selection phenomena in under-cooled melts: application to magnetic and refractory alloys of industrial relevance	Physical Sciences	Loeser
AO-99-108	Hydrodynamics of wet foams	Physical Sciences	Langevin
AO-99-110	CIMEX: Convection and Interfacial Mass Exchange	Physical Sciences	Legros
AO-99-111	Diffusion and SORET coefficients measurements for improvement of oil recovery	Physical Sciences	Legros
AO-99-114	Metastable solidification of composites: novel peritectic structures and in-situ composites	Physical Sciences	Herlach
AO-99-117	Columnar-Equiaxed Transition in Solidification processing (Cetsol)	Physical Sciences	Billia
AO-99-121	Ballistic and holographic 3-D high-resolution imaging of bone	Biotechnology	Hoffmann
AO-99-122	Bone metabolic studies in a combined perfusion and loading chamber	Biotechnology	Jones
LSS-003	Investigation of developmental pathways leading to bone formation and bone momeostasis by genetic dissection and functional analysis of osteoprotegerin in a transgenic fish model on Earth and microgravity environment	Biotechnology	Goerlich
LSS-006	Vascular endothelial cells in microgravity: gene expression, cellular energy metabolism and differentation	Biotechnology	Bradamante
LSS-015	A total converting and biosafe liquefaction compartment for MELISSA	Biotechnology	Verstraete
LSS-017	Closed-habitat environmental control sensors	Biotechnology	Boarino
LSS-018	Molecular tools for monitoring and control of (pathogenic) bacteria in advanced	Biotechnology	Krooneman
LSS-019	Biological air filter for air quality control of life-support systems in manned spacecraft and other closed environments	Biotechnology	Van der Waarde
LSS-034	A Biosensor to monitor radiation-induced DNA damage on the ISS: risk assessment for astronauts	Biotechnology	Walmsley
MED-007	A novel system for in-vitro detection of gravity effects on primary haemostasi	Life Sciences	De Marco
MED-023	Echography doppler assisted by robotic arm (EDRA)	Life Sciences	Arbeille
MED-027	Effects of simulated and actual microgravity on muscle function during explosive efforts	Life Sciences	DiPrampero
MED-028	Microgravity effects on human skeletal muscle function investigated by surface EMG and mechanomyogram	Life Sciences	Merletti
MED-030	Resistance training using flywheel technology for crew stationed in space	Life Sciences	Tesch
MED-031	Airway nitric oxide in microgravity	Life Sciences	Linnarsson

contribution is zero; for very high application potential, the ESA funding could be up to 300 kEuro/year.

The outcome of this arrangement is that ESA, industries and academic institutions each participate at approximately the same level in funding these projects (Fig. 3). The resulting scheme has therefore led effectively to the establishment of true Public-Private-Partnerships.

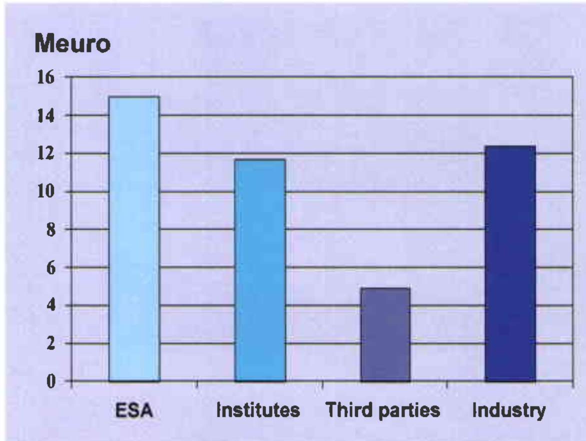


Figure 3. The distribution of the financial contributions to the costs of the application-oriented projects. The industries and the research institutes each contribute almost a third of the total project costs

Project details

The topics addressed in the 43 approved applied research projects cover a broad range (Fig. 4). An example is provided here for each of the Biotechnology, Health, Environment, (petro)Chemistry and (new) Materials categories.

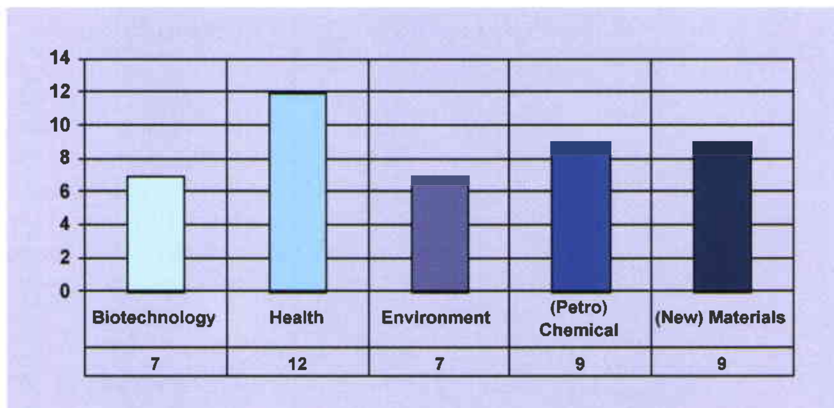


Figure 4. The topics addressed in the current set of 43 application-oriented research projects. Almost 125 European (non-space) industries are participating in these projects

Biotechnology: growing artificial tissues

Growing artificial human tissue for transplantation would be an answer to important medical problems. This would be true particularly if the starting material used cells directly from the patient. Such tissue would be free from the rejection currently encountered and would also be an essentially limitless supply.

Unfortunately, all attempts on Earth to make human cells grow *in vitro* in three dimensions seem to fail. Gravity is clearly a disturbing factor. Therefore, this project will attempt to culture human cells in a specifically designed bioreactor that can operate in weightlessness. The results of these experiments will help to unravel the cellular mechanisms underlying the growth of tissues in 3-D. The first trials will use a relatively simple tissue: cartilage. Cartilage transplants could help large numbers of people suffering from joint problems caused by sports accidents or diseases. Later, growth of more complicated tissues will be attempted.

In this example, two points should be stressed. First of all, the final objective of this project is not to grow tissues in space that will then be used for transplantation. Rather, it is hoped that the space experiments will lead to a method for growing functional tissues on Earth. Secondly, since clinical trials take a long time, this project, even if successful, will not lead to immediate breakthroughs in medical treatment.

Nevertheless, even if space experiments deliver only a few pieces of this complex puzzle, this project would already have proved its value.

Health: understanding, diagnosing and treating osteoporosis

One of the best-known effects of weightlessness on the human body is the loss of bone mass and structure. Once in space, astronauts can lose up to 20% of the calcium in their bones per year. This effect is not identical to, but closely resembles, the disease of osteoporosis. Obviously, this disease progresses much more slowly on Earth, but it has major consequences: it affects about 35% of women and 6% of men over 50 years of age.

Experiments in weightlessness are a good way to study the underlying mechanisms. In particular, advantages include the rapid availability of results and the fact that tests are done with otherwise completely healthy volunteers. Several projects are being supported by ESA; participants include university and hospital researchers, medical companies and developers of medical equipment.

Apart from real space experiments, tests are also being performed using bedrest studies, in which weightlessness is simulated by keeping volunteers in a 6° head-down tilt for extended periods. Recently, a record 90-day bedrest study involving 25 volunteers was organised by ESA, CNES and NASDA at the facilities of MEDES in Toulouse (Fig. 5).

The objectives of the research in this domain are threefold:

- understanding the fundamental cellular and physiological processes involved in bone mass and structure loss,

Figure 5. Dinner for one of the 25 volunteers in the 90-day bedrest study organised in 2001/2002 by ESA, CNES and NASDA

- developing new diagnostic tools for early recognition and monitoring of osteoporosis,
- testing new treatment methods, such as novel drugs or physical countermeasures.

Significant progress is being made in all areas. In particular, a novel exercise machine has been tested in bedrest studies and appears to be highly effective. Some new drugs show promise. Finally, a 3-D peripheral Quantitative Computed Tomography technique has been developed with good prospects for clinical application.

Environment: improving the efficiency of combustion

A 'classic' in space research is burning a candle in weightlessness. This simple experiment, in which the flame turns completely spherical and transparent blue, demonstrates the strong influence of gravity on the burning process. On Earth, the burning process gives rise to convection of the surrounding air, thus providing the traditional flame shape. This convection also means the burning is incomplete, while soot creates the yellow flame (Fig. 6)

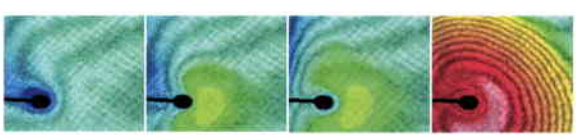


Figure 6. A typical example of a flame in weightlessness. The spherical shape and blue colour are due to the absence of gravity-induced convection

In spite of this apparently simple demonstration, combustion is a very complicated process. Numerous chemical reactions depend on local conditions such as concentrations and temperature, which in turn are determined by the flow velocities of the constituents. In space, the inherent flow velocity is negligible, but it is also possible to introduce artificial velocities using a controlled external airflow. These experiments can thus identify and quantify the influence of the various steps involved in the combustion process.

The results are of great interest for developing numerical models that predict how combustion proceeds under variable circumstances and geometries. Interested parties include companies who build power plants or car engines. They plan to use these improved computer models to optimise the efficiency or reduce the environmental loads of their designs.

(Petro)Chemical: increasing the yield of oil fields

Loosely related to the previous example is improving the accuracy of data used in analysing the contents of oil fields. Over geological timescales, the distribution of the constituents of an oil reservoir results from the dynamical equilibrium between:

- thermodiffusion driven by the geothermal gradient,
- diffusion driven by the concentration gradients,
- sedimentation driven by the hydrostatic pressure gradient (i.e. gravity).

From this it is clear that diffusion data are key to oil-reservoir numerical models developed by industry to optimise their drilling strategy. However, on Earth gravity prevents the measurement of the diffusive processes in multi-component systems, such as crude oil, in isolation.

In space, on the contrary, convection and stratification in multi-component mixtures is absent and these measurements can be made. The necessary equipment is in its final stages of development and the first measurements will be made during two missions later in 2002: the Soyuz Taxi mission of Frank De Winne to the International Space Station, and the Foton-M1 unmanned mission, both in October. If successful, more measurement campaigns will be planned. Some large oil companies are involved in this project, with several university groups.

(New) Materials: developing new casting techniques

In recent years, casting has developed from a rather straightforward activity to a very high-tech specialty. Today, very complicated moulds are used to produce, for example, entire engine blocks and other complicated structures. In order to fine-tune and guarantee the desired mechanical and other properties at each location in such a structure, detailed knowledge of the underlying solidification physics, and in particular the microstructure formation, is required.

Current computer models are not yet accurate enough to bridge the gap from the scientific microscopic length scale to macroscopic models useful to the casting industry. One of the main factors is the poor knowledge of the essential thermo-physical properties of liquid metals.

For example, even although molten iron is produced daily in enormous quantities, its very fundamental viscosity coefficient is known to an accuracy of only ±50%. Basically, only its order of magnitude is known (Fig. 7 provides an overview of relevant data). The reason for this low accuracy is that it is extremely difficult on Earth to obtain samples of pure molten iron. Owing to its high temperature and chemical aggressiveness, the walls of almost any container dissolve in the liquid metal and thus pollute it.

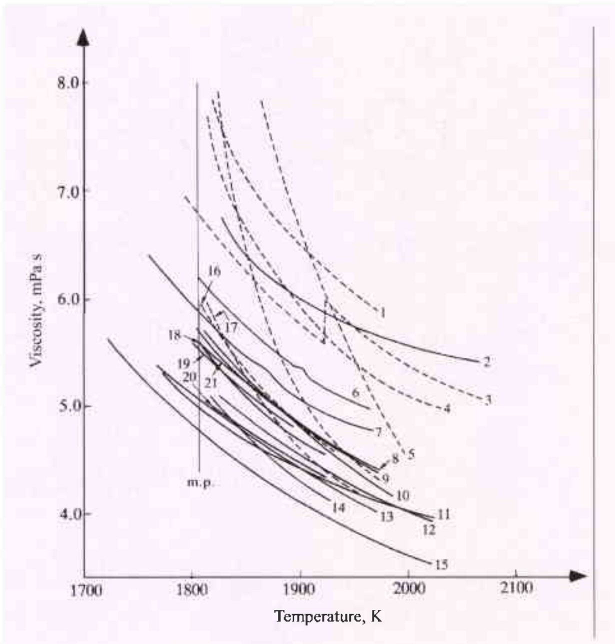


Figure 7. State-of-the art data on the viscosity coefficient of liquid iron

Under weightlessness, however, it is relatively simple to produce pure molten metal because, in principle, no container is necessary to hold the sample. With proper instrumentation, a sample can even be prepared in vacuum, and most of the important properties can be measured. The first trials are being planned for parabolic flight campaigns in the near future. For the longer term, specific equipment is being designed for the Space Station.

This theme is attracting very high interest from academic groups, and from a large number of companies. Indeed, a recent survey identified the need for this type of data from companies in the glass-making, enamelling, energy production, welding, foundry, casting, spray casting, secondary refining, alloy production and primary metal production businesses.

Future perspectives and conclusions

The above examples show that the emphasis of the applied research projects supported by ESA is not so much on production in space but on obtaining essential knowledge or data unavailable from Earth experiments. These projects are clearly in the pre-competitive R&D phase, but the significant interest from industry demonstrates their potential.

For the moment, the financial contribution from industry does not cover the launch costs, the development of the experimental facilities and, in particular, a share in the operational costs. It is to be expected, however, that as soon as the first successful experiments demonstrate the proof-of-concept, industries will be ready to increase their contribution to (partially) cover these aspects. Indeed, in some areas pathfinder projects are already being defined that could lead to a more commercial mode of operation.

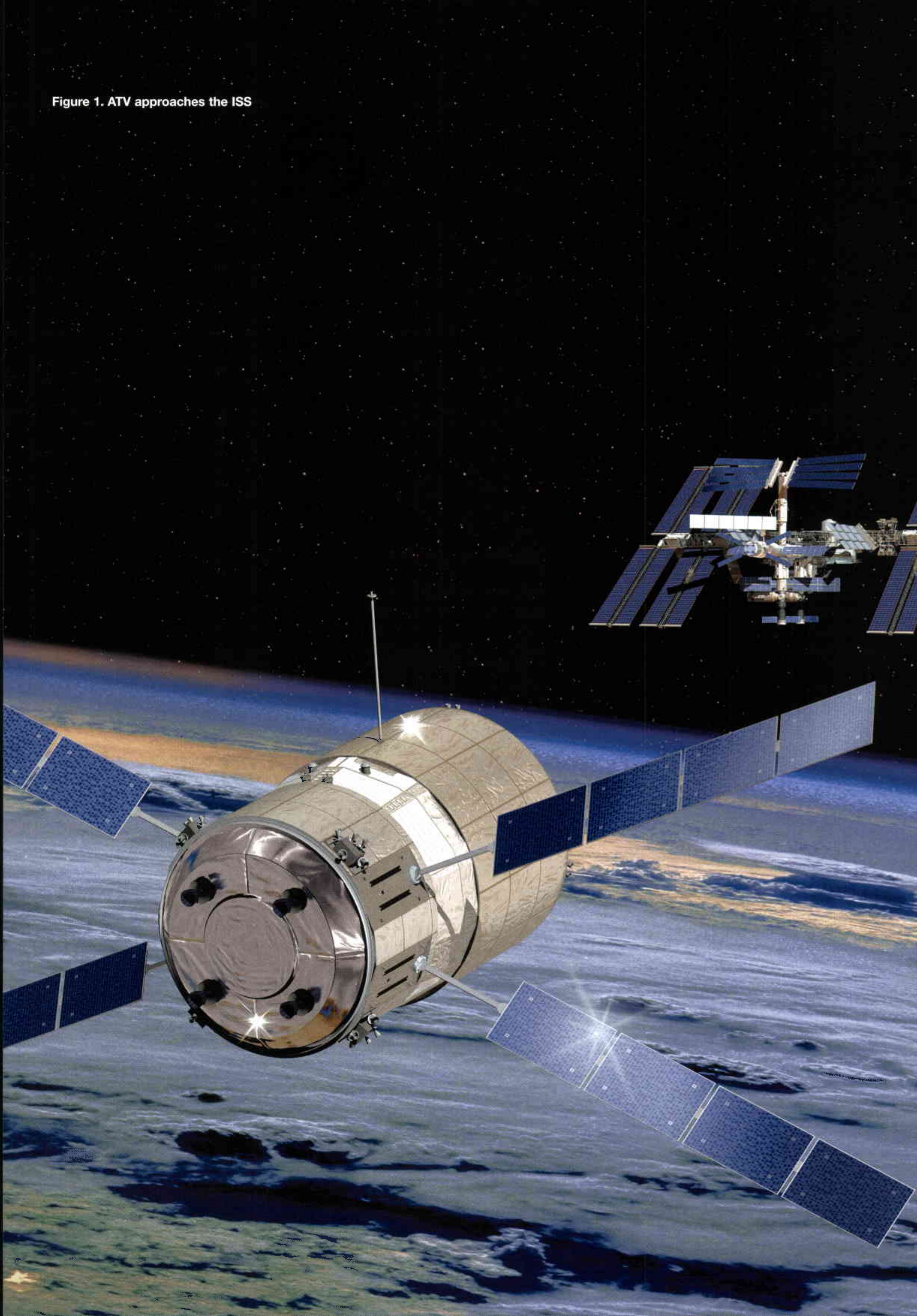
Finally, the current set of 43 projects have inherent properties that should attract funding from programmes of the European Community:

- there is an identified benefit for economy or society
- the knowledge obtained in these projects will improve European competitiveness and technological knowledge base
- the topics correspond well to the thematic priorities identified in the Framework Programmes of the EC
- all the projects show strong participation from industry and academic institutes in several European companies (one of the prerequisites for obtaining EC funding).

EC funding has already been obtained for two examples mentioned above. In one osteoporosis project, ESA is an active partner and is contributing its own resources, complementing those from the EC. From recent contacts with participants in other projects, it is clear that is strong motivation for such collaboration. An ideal tool for this would be the Integrated Projects, a new funding instrument defined by the EC and which will be first used in the 6th Framework Programme to be launched in November 2002. In such Integrated Projects, ESA would take the responsibility for the space-related costs and aspects, whereas the EC funding would be used to develop the Earth applications. Preparations for such arrangements are under way.

In conclusion, it can be said that a new chapter in life and physical sciences research in space has begun. Although space factories are not expected to appear in the skies soon, the space factor will definitely start to deliver benefits to Earth in the foreseeable future.

Figure 1. ATV approaches the ISS



Automated Transfer Vehicle (ATV) Structural and Thermal Model Testing at ESTEC

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The ATV Structural and Thermal Model (STM) test campaign began at the ESTEC Test Centre in October 2001. ATV's capabilities, mission, configuration and development logic are outlined. The STM Test Campaign and test objectives are then detailed. Some special requirements imposed by ATV's size are described. The main test results and lessons learned are summarised.

ATV description

ATV capabilities

The Automated Transfer Vehicle (ATV) being developed by ESA is an unmanned vehicle that can be configured to provide the International Space Station (ISS) with up to 5500 kg of dry supplies (e.g. hardware, food and clothes) and liquid and gas supplies (up to 840 kg of water; up to 100 kg of gases (air, nitrogen, oxygen); up to 860 kg of refuelling propellant). ATV can provide propulsion support to the ISS by using up to 4700 kg of propellant. The total net payload is estimated to be at least 7500 kg. Finally, ATV can also remove up to 6500 kg of waste from the Station.

At least eight ATV flights to the ISS are planned as part of the European contribution to supporting ISS operations (Fig. 1).

ATV configuration

The ATV vehicle is composed of two elements (Fig. 2): the spacecraft (SC; including solar array) and Integrated Cargo Carrier (ICC).

The ATV spacecraft comprises:
- the Separation and Distancing Module (SDM), which provides the mechanical interface with Ariane-5 and ATV's separation and distancing from the launcher;
- the Equipped Propulsion Bay (EPB), which accommodates most of the Propulsion and Reboost Subsystem (some thrusters are also located on the forward part of the ICC);
- the Equipped Avionics Bay (EAB), which accommodates most of the avionics equipment (some avionics items such as rendezvous sensors are located in the ICC and EPB);
- the Solar Generation System (SGS), which includes four 4-panel deployable solar wings, each with its own drive mechanism.

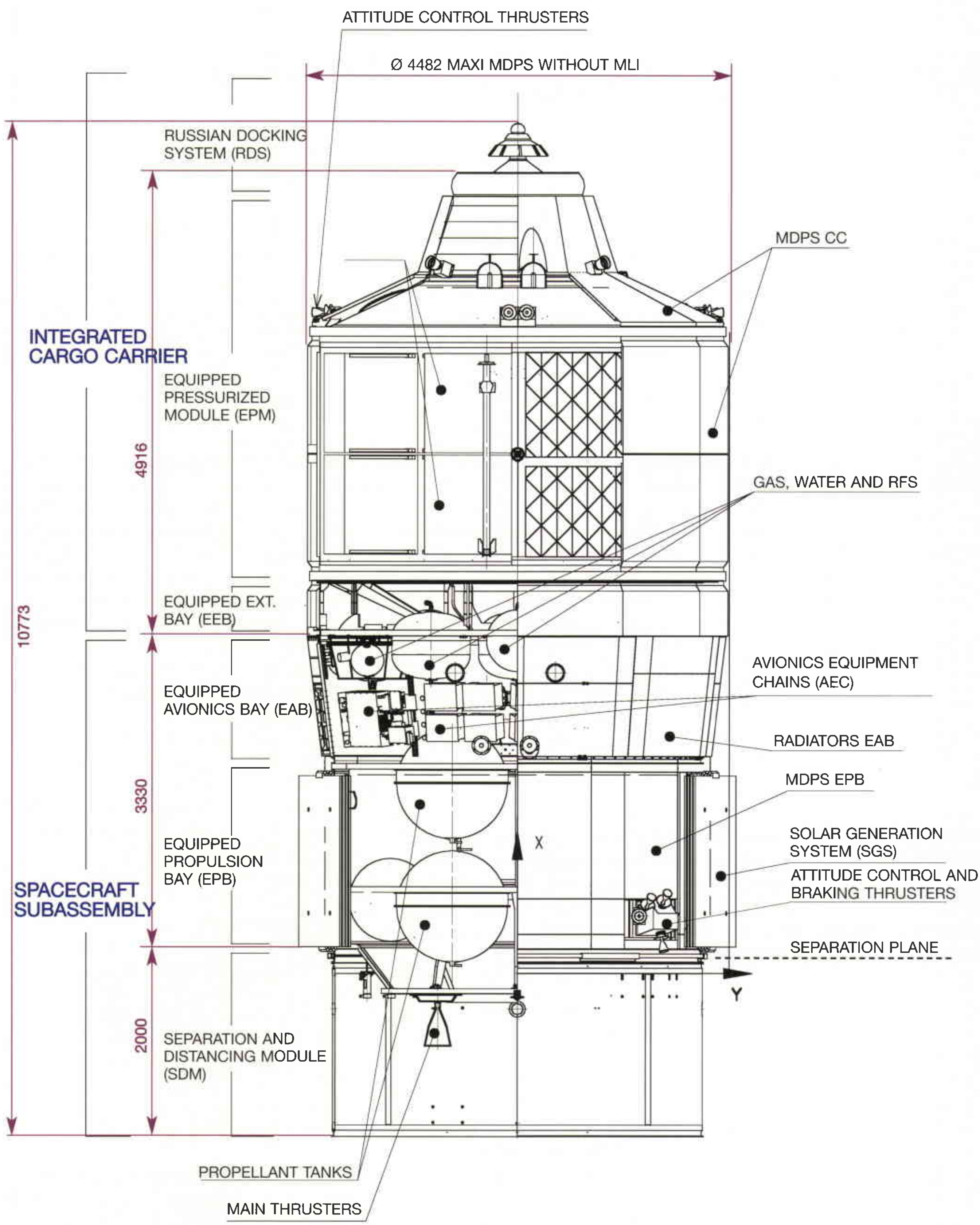
The ICC accommodates all cargo apart from the reboost propellant (carried in the spacecraft) and consists of:
- the Equipped Pressurised Module (EPM), which accommodates dry cargo in dedicated payload racks. ISS waste is carried for the destructive reentry part of the ATV mission;
- the Equipped External Bay (EEB), which is an unpressurised assembly to house water, gas and refuelling propellant tanks;
- the Russian Docking System (RDS), which provides capture and release for docking with and departure from the ISS. Several RDS models, including for the first ATV, are being provided by Russia as a barter for the European Data Management System that is currently operating in the Station's Zvezda Russian Service Module.

The ICC and SC are protected by the external Meteoroid and Debris Protection System (MDPS) shield.

ATV development logic and main system models

The ATV flight segment assembly, integration

Figure 2. ATV subassemblies and dimensions



and verification during Phase-C/D uses three system-level models: STM, Electrical Test Model (ETM) and Proto-Flight Model (PFM).

The STM is being used for environmental tests in the ESTEC Test Centre. After these tests, the SC will be subjected to static tests at Contraves (CH). The ICC external bay will be subjected to further dynamic and static tests (together with a flight-standard pressurised module). The STM pressurised module will be refurbished at Alenia (I) and eventually used for crew training at the European Astronaut Centre in Cologne (D).

The ETM is being used for functional qualification testing of the ATV and for a first set of vehicle/ground segment compatibility tests. After initial integration and electrical testing of the EAB ETM at Astrium SAS (F), the full ATV ETM (including the ETM models of the avionic equipment in the ICC and EPB) will be integrated at EADS Launch Vehicles.

The PFM, now named 'Jules Verne', will be subjected to the following environmental and functional tests:
- acoustic
- electromagnetic compatibility
- solar wing deployment
- clampband release
- thermal test (EAB level)
- final set of vehicle/ground segment compatibility tests
- complementary electrical and functional qualification tests
- functional acceptance.

The ATV Flight Segment prime contractor for Phases-C/D (development, manufacture, integration of first vehicle and associated ground support equipment, as well as ATV qualification) is EADS Launch Vehicles (Les Mureaux, F). The main contractors responsible for the subsystems and/or the ATV sub-assemblies are:
- Astrium GmbH (Bremen, D), propulsion and reboost subsystem, SC integration
- Alenia Spazio (Turin, I), ICC
- Astrium SAS (Toulouse, F), avionics sub-system, EAB integration
- Contraves (Zurich, CH), SC structure sub-system
- Dutch Space (Leiden, NL), solar array.

Testing at ESTEC

The main objective of the STM test campaign is to verify the vehicle's mechanical and thermal behaviour. Since many ATV components are either derived or directly reused from previous programmes, the dynamic tests are of particular importance for confirming their adequacy for ATV to save on delta-qualification or redesign. Another goal of the vibration tests (acoustic, sine) is to characterise the vibration environment experienced by ATV payloads in the payload racks.

The STM campaign began at the end of October 2001. Figure 3 shows the test sequence.

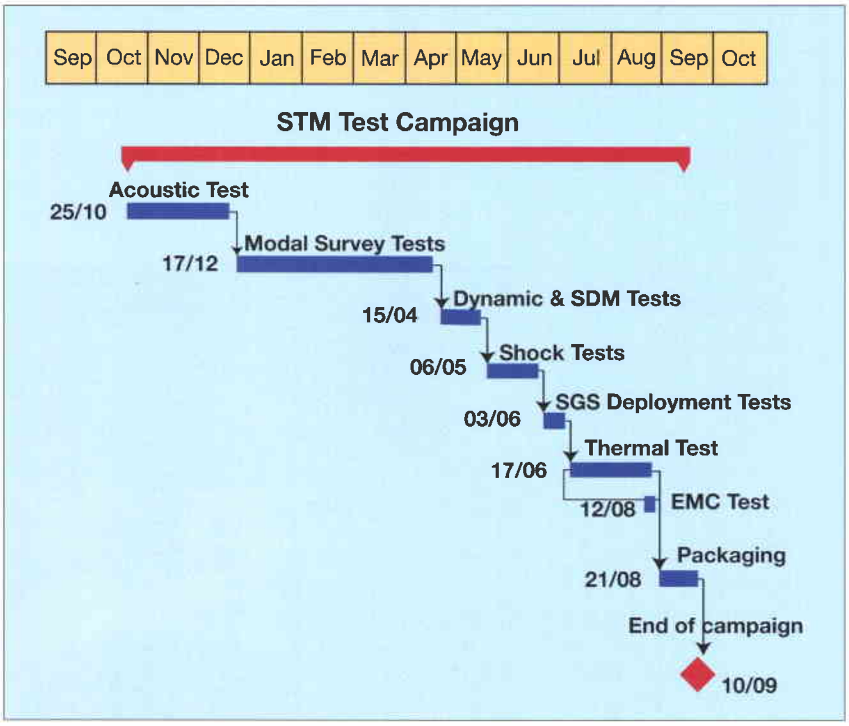


Figure 3. STM ESTEC test campaign sequence

STM representativity

The SDM model consists of a flight-representative structure, with a real clampband separation device equipped with connectors, but no distancing spring. The rest of the SC structure has only minor differences from the Flight Model. Its equipment mock-ups are dynamically and thermally representative; the stiffness at bracket interfaces is representative of the Flight Model, and there is 80% of the EPB harness and plumbing. Propulsion subsystem tanks are fillable structural mock-ups. The Thermal Control System is fully flight-representative. One solar wing is mechanically flight representative; the other three are simulated by single-panel mock-ups (identical mass and area as folded wings).

The ICC STM is dynamically representative of the Flight Model. The EPM (replaced by a special mock-up for thermal testing) structure includes a cylindrical shell and aft and forward conical parts. The EEB shows minor differences with respect to Flight Models. Racks are flight-standard. The Russian Docking System (RDS) is a mechanically and thermally representative mock-up. The ICC forward cone features a mechanical mock-up of a rendezvous sensor, on its dedicated support. ICC gas tanks are structural models with masses representative of filled tanks. Refuelling System (RFS) kits and water tanks are fillable structural models, with dummy valves and partial plumbing.

Acoustic test

Characterisation of the vibro-acoustic response of ATV to the acoustic levels induced by the Ariane-5 launch and flight was the major requirement of the acoustic test. The final goal was to compare acoustic and random vibration levels to those specified for ATV's major components and equipment. Tests were performed in December 2001 in the Large European Acoustic Facility (LEAF) at ESTEC.

Figure 4. ATV on the Acoustic Stand in LEAF

ATV with a total mass of 15 t (low loaded configuration) was mated with the Acoustic Uncoupling Stand (AUS, Fig. 4). This adapter dynamically uncouples ATV from the ground, as well as positioning it inside LEAF's homogeneous acoustic field. Uncoupling was achieved at the top of the adapter through rubber isolator mounting pads. A dry-run test involving the AUS alone was performed a few weeks before the STM test itself.

The test sequence was:
- low-level run: overall level 141 dB for 66 s
- intermediate-level run: overall level 143 dB for 60 s
- qualification-level run: overall level 147 dB for 120 s
- low-level run (to check sensors' individual responses and to assess structural integrity after the testing): overall level 141 dB for 60 s.

Achievement of homogeneity and the specified test spectrum took less than a minute for each test run. After the first run, microphone positioning was optimised; they were moved further from the STM, outside the acoustic homogeneous field. This unusual setting was due to the STM's size, which fully occupied the LEAF acoustic homogeneous field. During the qualification-level run, nitrogen aerodynamic noise at 4 kHz in the LEAF made the target input level in this non-critical band impossible to tune precisely (higher levels than required were achieved).

All these tests were successfully performed within 4 days. Qualification random levels for equipment are in the process of being confirmed by test-result analysis.

Modal survey

The test characterised the global dynamic behaviour of the complete ATV: the main longitudinal and lateral structural eigenmodes of the ATV, and (when uncoupled) the eigenmodes of the vehicle's main components. Eigenfrequencies and shapes, effective and generalised masses and damping factors of the eigenmodes were produced by modal survey tests. These results are being used for updating the ATV mathematical model for ATV/Ariane-5 coupled load analysis.

The modal survey logic was based on two test configurations with different fluid and dry-cargo loadings. In reality, ATV will carry a wide range of payload combinations. Both configurations had a mass of around 20 t. The first used an extreme payload distribution chosen to produce maximum dynamic coupling between SC and ICC. The second was closer to a probable payload distribution for the first ATV flight, with clearly separated SC and ICC eigenmodes. The STM was interfaced with the ground by the Mechanical Interface (MIF) test adapter. Its double conical shape ensured that the high lateral eigenfrequency did not interfere with ATV's main eigenmodes during the tests.

Two methods were possible for performing the tests:
- local exciters in LEAF, with its seismic block of around 2000 t of concrete. The test principle

would then be phase resonance (direct modal identification): broad-band low-level sweeps, followed by tuned sine excitation (for identification of primary target eigenmodes), and narrow-band sweeps (for determination of modal parameters and non-linearities). Further target eigenmode information would be available through broad-band sweep analysis
- the HYDRA hydraulic shaker (3-axis excitation through eight actuators of 630 kN; four on the vertical axis, two on each lateral axis). The approach would be phase separation with broad-band low-level sweeps through sine excitation for eigenmode identification, customised broad-band sweeps and analysis to determine modal parameters and assess non-linearities. Use of HYDRA implies recording of temporal data, requiring further analysis to derive Frequency Response Functions.

The choice was driven by one HYDRA main constraint: lateral excitation along one axis results in non-negligible 3-axis excitation owing to 'cross-talk' effects. In order to limit risks for the success of the test, the decision was taken to use local exciters for lateral excitation in LEAF, and to use HYDRA only for longitudinal tests since this allowed higher load levels, which are useful for the estimation of damping.

Following acoustic tests, the LEAF lateral test on the first configuration started in February 2002. IABG provided four exciters: two of 2.2 kN were placed at the SC/ICC interface level and two of 7 kN were placed at the ICC upper handling ring level. The IABG data acquisition system recorded information from around 580 accelerometers and 50 strain gauges that measured SC/ICC and SC/adapter interface force fluxes. Figure 5 shows the test set-up.

Since the MIF adapter was designed to interface with the HYDRA table, its use in LEAF required a special metal plate, bolted and torqued to the ground, onto which the MIF was fixed. To ensure proper clamping of the test specimen to LEAF's seismic block, an epoxy layer was laid between the plate and ground. The test configuration was finally set up after a floor compliance measurement with only the MIF mated via the metal plate to the ground.

The lateral testing took 4 days, including broad-band and narrow-band sweeps, and identified all target eigenmodes. Raw results were corrected with respect to ground effects (unsymmetrical stiffness at the base of the test set-up) using forces and accelerations measured on the test floor and test adapter.

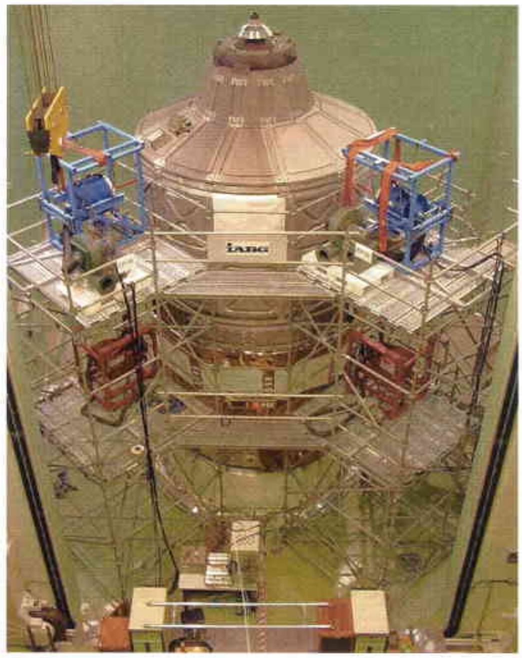


Figure 5. Lateral modal survey test set-up with ATV on MIF

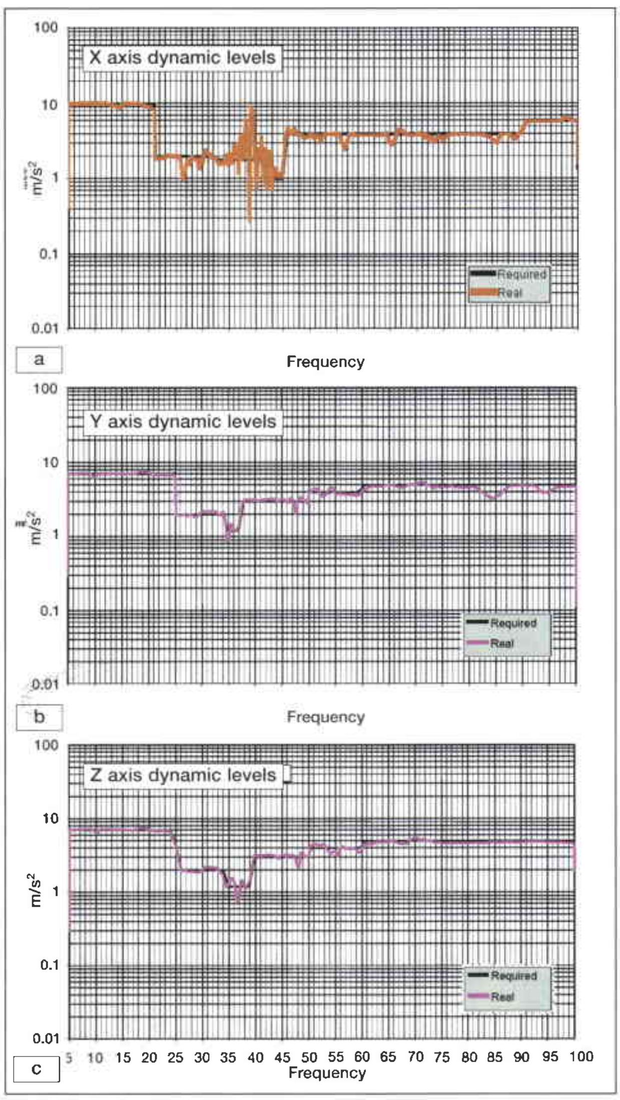
A quick longitudinal test was added in LEAF using one local exciter hanging from a crane and mated with the ICC upper handling ring. Its purpose was to prepare for HYDRA runs by identifying primary longitudinal target eigenmodes.

The transfer of STM and MIF to HYDRA finally allowed the main longitudinal runs to begin (Fig. 6). Both configurations underwent longitudinal modal survey tests on HYDRA and

Figure 6. Longitudinal modal survey test set-up on HYDRA

provided satisfactory results, confirming the test predictions.

Further lateral tests were performed on HYDRA. Owing to the complex rocking motion of the table in specific frequency bands, the individual behaviours of ATV and the table proved difficult to decorrelate, so it was not possible to assess precisely the associated damping factors. However, those runs confirmed the eigenfrequencies of the first bending modes.



Figures 7a-c. Achieved levels for dynamic tests

It was considered that these tests had provided sufficient information, so the test sequence was shortened and the second set of LEAF lateral testing was cancelled.

Dynamic qualification

Considering ATV's high mass (up to 20.75 t) and ESTEC's testing capabilities, the initial logic was of qualification in stages: Finite Element Model (FEM) updating after modal test, updated Ariane-5/ATV coupled-load analysis to assess dynamic qualification levels, test predictions for the SC and ICC separately, and separate dynamic tests for the SC and ICC. However, given the good correlation between the STM FEM predictions and the modal results, and HYDRA's proven capability during modal survey tests to apply the required dynamic levels to the combined (ATV and MIF) mass of 24 t, the opportunity was taken to make use of the full STM configuration (without SDM). Thus, the new logic consisted of performing iterative runs to achieve levels as high as possible, taking into account the maximum allowable levels for ATV's main components and critical equipment, as well as the expected Ariane-5 dynamic environment. Test-result evaluation and post-test analyses would then verify that ATV can withstand the Ariane-5 environment with adequate margins.

After analysis of the modal survey results and following a thorough ATV inspection, some additional sensors were integrated into the STM. Tests along the X- (vertical) and Y- (lateral) axes were then first performed: intermediate-level runs (around 80% of flight limit levels) to record all available channels, then assessment of transfer functions for all measurement points to deduce the next run at increased levels.

Coupling between the shaker and the test article resulted in artificial damping at the eigenfrequency of the first ATV bending mode. The input levels were adapted around this eigenfrequency to obtain the correct force at the ATV interface. Interactions between the test article and the shaker table induced control difficulties, and therefore limited the input levels at specific frequencies. In this case, the finally applied levels were adjusted to reach qualification levels on heavy items such as propellant tanks.

These two first dynamic qualification tests were completed successfully. Given the test configuration symmetry, Z-axis input levels were the same as those specified along the Y-axis. Figures 7a-c show the final applied input levels at ATV's base. Differences between the specified and achieved levels were caused by either notching or control effects. The qualification testing in three axes was considered to be successfully completed at the end of April 2002. The final Ariane-5/ATV coupled-load analysis aims to confirm the input levels used during the tests.

Thanks to HYDRA, the ATV STM is the heaviest and largest specimen ever subjected to high-level sine vibration testing for an ESA programme.

The sine-test specifications for equipment were refined on the basis of the results of the qualification tests. In particular, qualification vibration specifications for ATV's Russian equipment, originally qualified for launch on Russian vehicles, are in the process of being confirmed. This would avoid modification of those items when used on ATV.

Mechanical qualification testing will be completed by static tests on the primary structure and by pressure integrity tests on the pressurised module.

ATV (including SDM) modal test

The 2 m-high SDM cylindrical adapter was developed for ATV to interface directly with Ariane-5's 3936 mm diameter. The SDM adapter includes a clampband separation system that was developed specially for ATV's large diameter. This adapter uses the new 'clamp ring separation system' technology, which offers the advantage of generating low shock levels.

Figure 8. ATV (with SDM) modal tests on HYDRA

In order to assess the influence of the adapter on ATV's global dynamic behaviour, it was decided to perform additional characterisation tests. The complete ATV launch configuration (including SDM) was vibration-tested on HYDRA in the longitudinal and lateral directions (low levels, X and Y excitations; Fig. 8). The tests verified the compliance of ATV's (including SDM) first lateral eigenfrequency with Ariane-5's requirements (i.e. this eigenfrequency should be high enough to avoid influencing launcher behaviour).

Shock tests

Shock tests involved a complete ATV/SDM configuration hoisted in the HYDRA Preparation Area (Fig. 9). The first shock test (the 'Shogun' test) dealt with the ATV external shock from the jettisoning of Ariane's fairing. A dedicated pyrotechnic device (Shogun) was provided by Arianespace to generate these representative shock levels at the SDM interface. This device was made of a pyrotechnic linear cord charge inside a weakened aluminium structure (3936 mm diameter). The shock wave was generated by the expansion of the tube causing a controlled rupture of the lower flange screw section. A spacer (a 260 mm-diameter cylinder developed for ATV ground integration operations) provided the interface between the SDM and Shogun, and was intended to create the proper shock level at SDM's lower interface.

Figure 9. ATV shock test set-up in the HYDRA preparation area

A dry-run at the end of March 2002 demonstrated that Shogun produced the required shock levels. The STM Shogun test was successfully completed at the end of May.

The second shock test concerned the clampband release. The Shogun and spacer were removed, and SDM was held to prevent its lower half falling after release. The test used shock sensors and two high-speed cameras (1000 frames/s). The clampband was successfully released after exposure to the Shogun shock.

The shock transfer functions from the bottom of the ATV to the most critical equipment were measured. It was verified that the shock at the base of ICC produced negligible levels for this module's equipment. The shock levels on the other equipment will be derived by post-test analyses using these transfer functions. The main goal of the second test was to measure the shock levels at the most critical equipment interfaces. Further analysis incorporating the results of the two tests will validate the shock specifications for ATV's various elements and confirm, where necessary, the system margins.

Figure 10. Solar wing under the deployment rig

Solar array deployment
An associated goal was assigned to the acoustic and shock tests: the application of these environments to a stowed solar array in order to verify its correct deployment. The deployment test took place following the end of shock tests with the SC horizontal (and without SDM or ICC). A rig held the wing to compensate for gravity (Fig. 10). The deployment was successful. The times for cutting the hold-down cables and for wing deployment were within specifications. Deployment was therefore demonstrated after exposure to the acoustic, shock and dynamic qualification environments.

Thermal balance test
Checking and upgrading ATV's Thermal Mathematical Model, to be used for ATV qualification, will be achieved via global thermal characterisation in vacuum of a test specimen thermally representative of ATV under dissipative and environmental thermal loads.

The semi-active Thermal Control System (TCS) is based on Active Fluidic Cooling Units (AFCUs) containing heat pipes. The verification of its performance required the characterisation of the AFCU heat rejection maximal capacity in a hot environment and of the AFCU maximal insulation in a cold environment. The thermal test also verified the thermal control algorithms and thus the capacity of this TCS subsystem to maintain the vehicle within required limits. Secondary objectives, such as identification of the heat leak sources and confirmation of the heat leak budget, and thermal characterisation of the docking system and structure under thermo-mechanical loads, were also addressed.

This was the final STM test at ESTEC, in the Large Space Simulator (LSS) between the end of July and early August 2002. Severe thermal requirements drove the ATV configuration inside LSS (Figs. 11 and 12):
- keeping the heat pipes horizontal was critical for them to work. This meant that ATV had to be vertical inside the LSS, and therefore heated from the side by the solar simulator
- the STM had to be illuminated by the solar beam to simulate the hot and cold transient and steady flight phases, and thermal cycling. The 6 m-diameter beam required replacing the EPM (pressurised, temperature-controlled module, behaving only as a thermal inertia) with a smaller mock-up
- the three sides not in direct view of the Sun had to face controllable, simulated Earth thermal fluxes. This was supplied via a structure in three planes (Figs. 11 and 12 show two). Each plane of this EASi (EArth Simulator) consisted of 15 individually heated panels. The complete assembly was mated to the LSS seismic platform through a support ring
- the aft side had to face a simulated Sun and deep space (the LSS seismic platform is uncooled). This SORSi (SOlar Rear Simulator) was equipped with heaters and liquid-nitrogen circulation for the different test-phase needs.
- the Thermal Test Stand connecting the STM and LSS platform minimised the thermal

fluxes between the two, as well as limiting interference with the LSS walls. This was achieved by a tubular lightweight structure with controlled thermal properties (thermal isolation, control of interface temperatures, multi-layer insulation).

As probably one of the most complex parts of the STM campaign, the thermal test also involved numerous electrical lines dedicated to:
- supplying 55 kW to more than 200 main lines for the heaters that simulated equipment power dissipation inside the STM, and for the heaters that guaranteed the thermal environment and boundary conditions for ATV or test adaptation interfaces
- acquisition of measurements from more than 800 thermocouples dedicated to measurement or control
- control of the AFCUs.

Additional activities
Some tests and measurements, though not directly associated with the environmental tests themselves but linked to operational verification, were added during the various phases of the STM test campaign. Indeed, the STM integration and test operations prefigure activities to be performed with the first Flight Model, either during its test campaign at ESTEC or during the launch campaign at Kourou, French Guiana.

Knowing the time and manpower required for each activity will allow the schedule for ground processing at Kourou to be refined. Throughout the test campaign, the large size of the ATV elements and the Mechanical Ground Support Equipment (MGSE) compared to that of the ESTEC cleanrooms led to numerous movements within the test facility. For example, tilting the SC from vertical to horizontal requires a ground area of about 6 x 9 m^2. Figure 13 highlights the size of the ICC container. The lessons learned in using the MGSE will help in laying out the integration and check-out area in the new S5 building at Kourou.

The STM test campaign also involved integrating ATV's major subassemblies (SC, ICC, SDM) for the first time (Fig. 14). This verified the interfaces between such large structures. Some of the techniques developed for STM will be used for Flight Model integration and operations in Europe and Kourou. For example, the AUS will be reused as an ATV integration and transfer stand.

Three operational verifications were also carried out on the SDM:
- characterising the evolution of clampband tension during the various integration

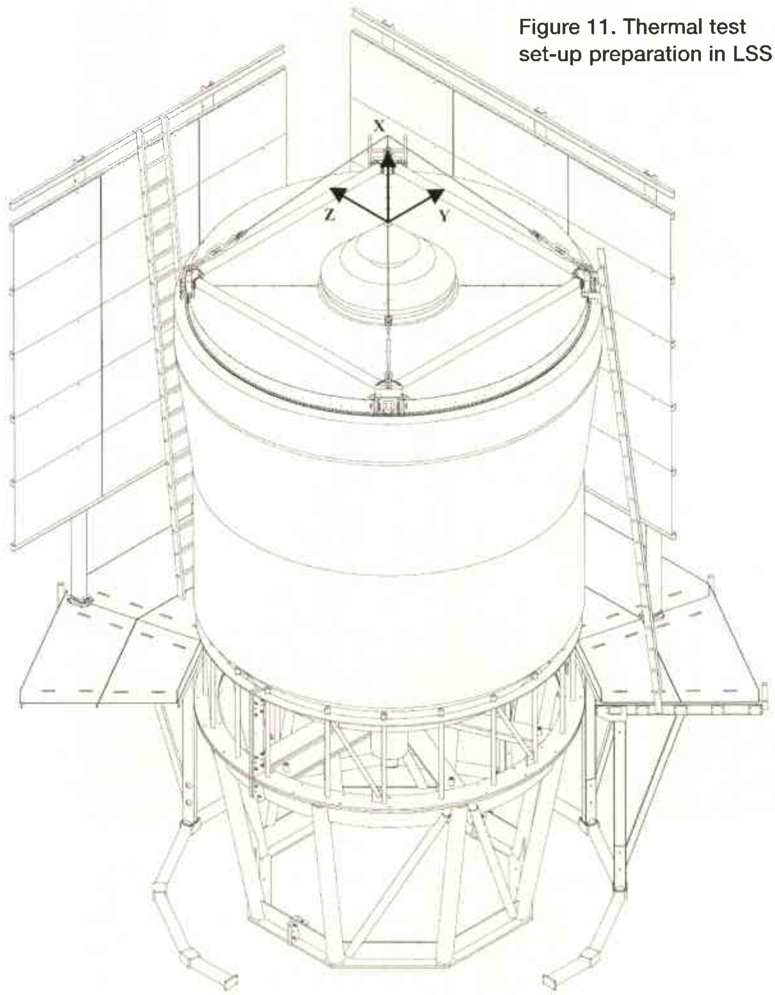


Figure 11. Thermal test set-up preparation in LSS

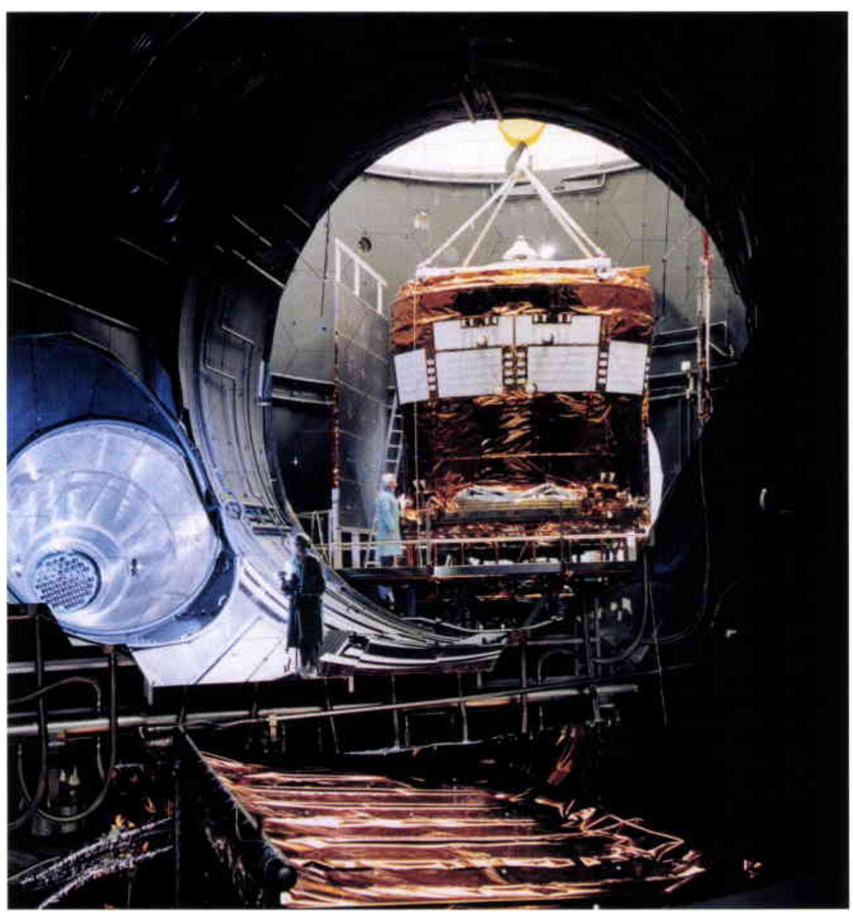


Figure 12. The ATV STM in ESTEC's LSS before thermal-balance testing

Figure 13. The ICC container is unloaded from the Beluga aircraft at Schiphol airport

operations. This tension was measured before and after the mating of the SDM with the spacer and the SC at, respectively, its lower and upper interfaces. Additional measurements were performed with and without ATV's mass on it (ATV hanging from the overhead crane). The goal was to verify the possibility of tensioning the clampband before PFM filling operations. The mathematical model was updated from the results

- measuring the geometry of SDM's lowest interface (when mated with the rest of ATV) to verify Ariane-5/ATV integration

Figure 14. Preparing for the first mechanical integration of ATV

- verifying the mating of the SDC (Separation and Distancing Cylinder, which is SDM's lower part) and the SES (SEparation System, which is SDM's upper part) when ATV is fully integrated.

The alignment of some elements of ATV Guidance Navigation and Control (GNC sensors and thrusters) is critical for the robustness of the flight control algorithms. Before and after each environmental test, the position and orientation of these elements were measured via videogrammetry in order to assess the impact of the applied environment.

Finally, a short electromagnetic (EM) test was performed using the thermal test configuration to measure the EM-shielding effectiveness of the EAB structure. The EM field was generated around the test object and specific test antennas allowed characterisation of the EM field inside the avionics bay. The results showed that the ATV structure provides the required attenuation of external EM fields.

Conclusion

The STM test campaign proved to be very intense. In addition to its own teams, EADS Launch Vehicles managed and coordinated teams from ETS (logistics, test logistics), Astrium (mechanical and fluidic operations), IABG (modal and dynamic tests), Arianespace and Intespace (shock tests) and other ATV subcontractors (Alenia, Contraves, EADS CASA, Dutch Space, APCO). ESA, as ATV customer, performed programmatic and technical monitoring. Numerous decisions had to be taken 'on the spot', making use of available materials and means. All the challenges were successfully met thanks to the efforts and constructive ideas of these teams, and the STM test campaign is expected to be completed by mid-September 2002, 2 months ahead of schedule. All involved are to be thanked for their dedication and commitment. This ESTEC campaign was the first involving ATV and all the related ground support. It offered a unique opportunity to check most of the critical mechanical operations that will be required for the flight operations in Europe and Kourou. The data gathered during this test campaign pave the way for the ATV Critical Design Review in April 2003 and for the PFM 'Jules Verne' ESTEC test campaign and Kourou operations.

Acknowledgements

The authors thank all their colleagues who, through their comments, contributed to this article.

Modelling ATV–TDRSS Communications at the International Space Station

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When the Automated Transfer Vehicle (ATV) docks with the International Space Station (ISS), the interactions between the ATV's S-band antennas and the large components (modules, solar panels, thermal radiators, etc.) of the ISS can significantly affect communication with the Tracking and Data Relay Satellite System (TDRSS) due to induced multipath effects. Extensive electromagnetic modelling has been used to establish that there will be sufficient margins for interference-free communication sessions during every ISS orbit.

Introduction

This article describes an efficient way to model the radiation of S-band quadrifilar helix antennas mounted on the ATV and operating when it docks with the ISS. This electromagnetic modelling is particularly critical because of the overall dimensions of the ATV-ISS system vis-à-vis the S-band wavelengths and the continuous rotation of a number of solar-generator and thermal-radiator panels to track the Sun's position.

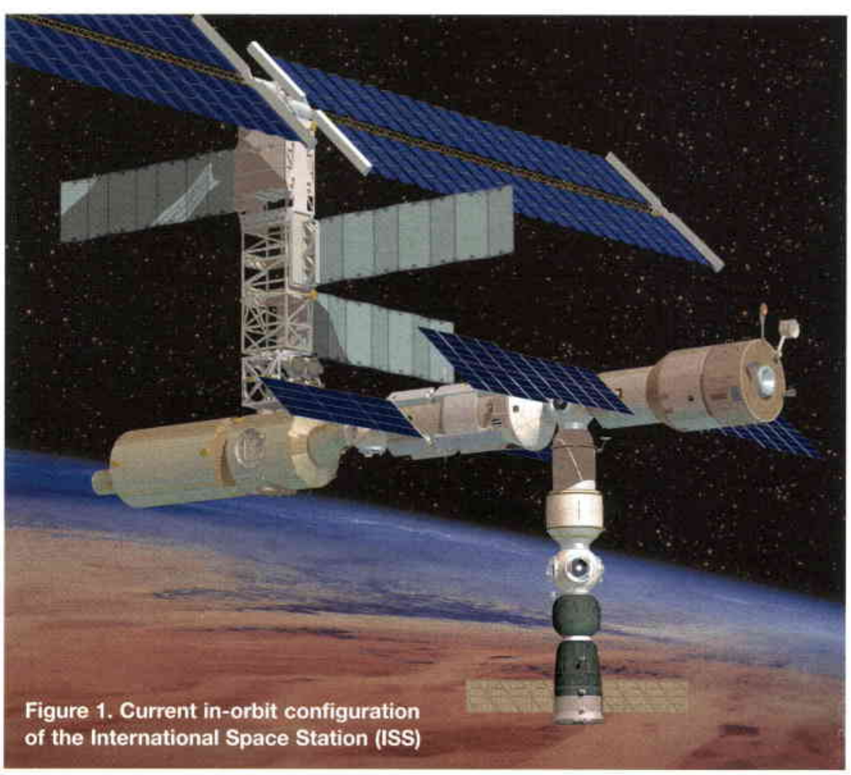
Figure 1. Current in-orbit configuration of the International Space Station (ISS)

The ISS is currently being assembled in orbit around the Earth (Fig. 1) and, when completed around 2006, the huge complex will be the largest ever structure in space, stretching over 100 metres and sprawling across an area the size of a modern football stadium.

ESA, NASA and the Russian, Japanese and Canadian Space Agencies are the international partners involved in the project. In addition to serving as a base for future space exploration, the ISS will be a laboratory for the scientific community where weightlessness and the unique environment of space will open up new areas for long-term research, including medical studies and the development of materials and manufacturing processes not possible on Earth. The main characteristics of the ISS are summarised in Table 1.

Table 1. Main characteristics of the ISS

Partners	USA, Russia, Europe, Canada, Japan
Laboratories	Six
Permanent Crew Capacity	Six/seven
Orbit	90 minutes to circle Earth
Inclination	51.6° to the Equator
Altitude	400 km (average) above Earth
Dimensions	108 m long x 80 m wide
Mass (weight)	455 865 kg
Living Volume	1200 m^3

The ATV is a large Automated Transfer Vehicle to supply the ISS. This new vehicle (Fig. 2), scheduled for an initial test flight in 2004 on Ariane-5, will dock with the Station's Russian Service Module. The ATV weighs 21 750 kg at launch, including 9500 kg of payload that includes food, water and oxygen for the crew, instruments and hardware for the Station, and propellant. Some 4000 kg of the propellant will be used to re-boost the Station to a higher orbit at regular intervals; another 860 kg will be transferred to the Station for its own attitude and orbit control. Like a classical spacecraft, the ATV is equipped with avionics, navigation and propulsion, and powered by solar panels. It will carry a separate pressurised payload container to which the crew will have access when docked to the Station (Fig. 3).

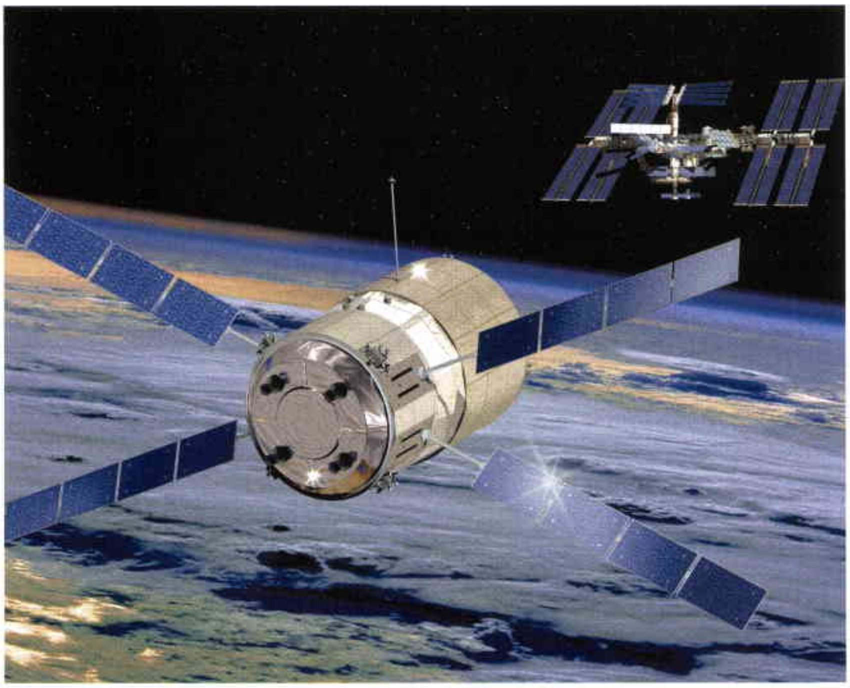

Figure 2. The Automated Transfer Vehicle (ATV)

An accurate electromagnetic simulator

Most of the previous electromagnetic studies devoted to this topic were based on simple geometrical models obtained by replacing the entire structure, composed of the ATV and the ISS, with only the largest components (less than ten elements). Consequently, the interactions between the ATV and ISS had been simulated with only limited accuracy. The first step in our analysis was therefore the generation of a new geometrical model composed of around one hundred elements, including all of the solar panels, all of the thermal radiators and the main modules making up the ATV and the ISS (Figs. 4 and 5).

In particular, in Figure 5 the y-axis is oriented along the central truss of the ISS, the x-axis is oriented like the ATV's x-axis along the velocity vector, whilst the z-axis, oriented to Earth, is perpendicular in the chosen view to the solar panels. The ATV appears in orange on the left side, the large American solar panels are in blue, with their main axis x-oriented, the Russian solar panels, which are y-oriented, are also in blue, and the large thermal radiators are shown in black (in two planes parallel to the plane y = 0).

It is important to note that while flying around the Earth the ISS continuously assumes a different orientation with respect to the position of the Sun. Consequently, in order to track the Sun, the solar panels and thermal radiators have to rotate to remain, respectively, perpendicular and parallel to the Sun's rays. Figure 5 actually relates to an extreme case in which the Sun lies exactly in the direction of the –z axis.

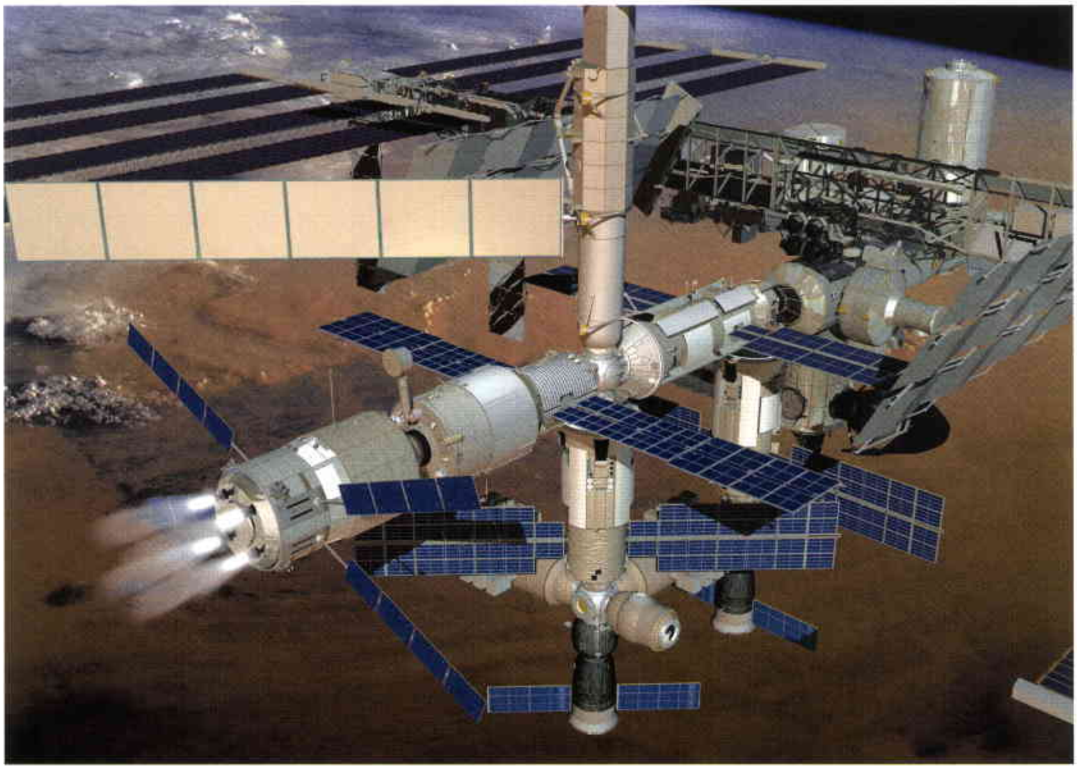

Figure 3. Artist's impression of the ATV docking with the ISS

Once a good geometrical model has been established, the second step was the realisation of the electromagnetic simulator. Firstly, this involved characterising the electromagnetic properties of the materials composing all of the modules, and then simulating the electromagnetic interactions between the ATV-mounted antennas and the metallic structures of both the ATV and ISS. In fact, the modules composing the ATV-ISS system can be considered perfectly conducting. The two sides of the solar panels exhibit different reflecting properties, the upper sides being composed of photovoltaic arrays, and the under sides being just a metallic surface. In our analysis, the solar panels and thermal radiators are also considered as perfectly conducting metallic plates characterised by a zero thickness.

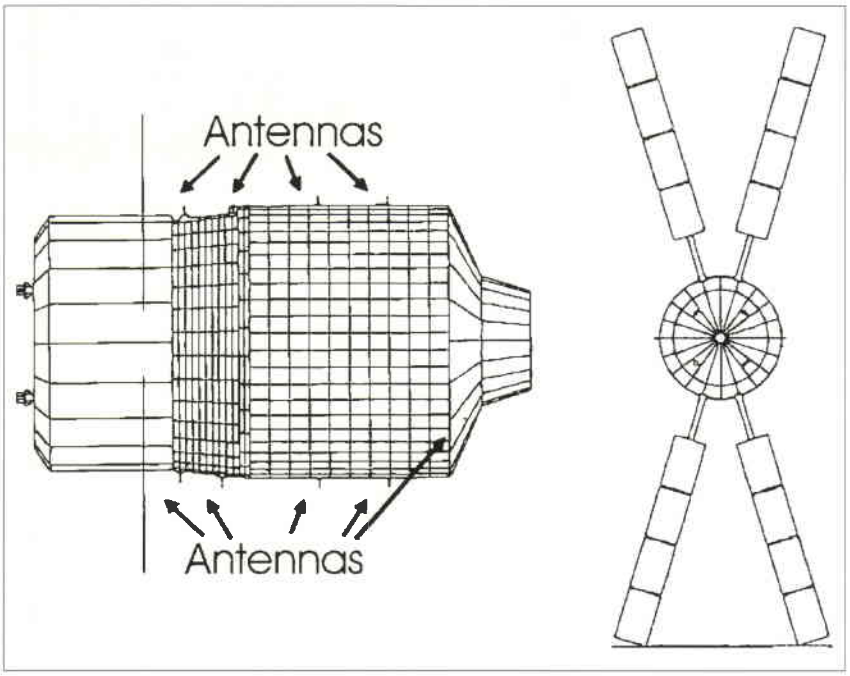

Figure 4. The geometrical modelling of the ATV and its antennas

Our work focused on the circularly polarised S-band antennas responsible linking the ATV-ISS and TDRSS systems. The frequencies chosen for the forward and return links were 2106.4 MHz and 2287.5 MHz, respectively. The antenna selected to establish the communications link was the quadrifilar helix unit shown in Figure 6. Its radiation pattern was shown in several experimental tests, performed by Astrium and RYMSA, to suffer only weak degradations in the presence of the ATV structure. The measured pattern of the isolated helix antenna was compared with that for the same antenna mounted over a cylindrical mock-up structure simulating part of the ATV module.

The ATV and the ISS are too large, in terms of wavelengths, for a rigorous full-wave analysis to be implemented. However, the ray-based Uniform Geometrical Theory of Diffraction (UTD) is particularly suited to managing the interactions between large structures that include metallic plates, cylinders, cones and similar components. The commercial code NEC-BSC IV (by Ronald J. Marhefka of Ohio State Univ.) allows one to take into account several ray contributions, including multiple reflections, diffractions from edges, wedges, corners, etc. (Fig. 7).

The speed of the electromagnetic simulator is particularly important in this type of analysis because the radiation from the S-band antennas has to be estimated for several possible orientations of the solar panels and thermal radiators as they continuously rotate. To introduce the S-band antennas into the electromagnetic characterisation, the measured radiation pattern relevant to the free-space helix antenna has been inserted in the UTD analysis as an equivalent source located

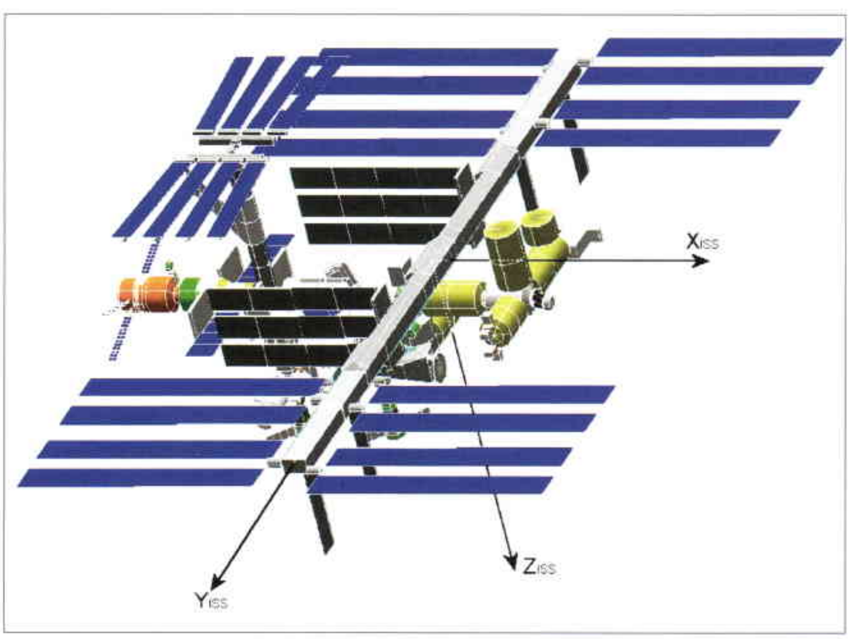

Figure 5. Elements included in the electromagnetic model of the ISS

Figure 6. The quadrifilar helix antenna on the ATV

exactly where the antenna is sited. This can be considered a hybrid UTD-measuring technique.

It has been verified (by EADS and Astrium) that, by evaluating the UTD interactions between the equivalent source and a cylindrical metallic mock-up, one obtains results really close to the measured results relevant to the configuration composed by the real helix antenna and the mock-up.

As previously mentioned, to completely characterise the radiation properties of the S-band antennas mounted on the ATV, a great number of simulations, corresponding to different orientation of the solar panels and thermal radiators, are required. The calculation times needed to run the electromagnetic simulations are therefore extremely important and the UTD modelling procedure was selected also for this reason.

It is important at this point to introduce three elements that play a significant role in the radiation mechanism, because of their proximity to the ATV. They are: (i) the vertical white mast shown in Figure 7, which is the Science Power Platform (SPP) core, a Russian supporting element; (ii) the Russian solar panels, which are the small horizontal blue panels near the TDRSS satellite at the top of the figure; and (iii) the Russian SPP thermal radiator, which is the horizontal rectangular component made with six rectangular plates. In several cases, these Russian elements create more electromagnetic interference than the huge American solar panels (the large blue panels with an oblique orientation in Fig. 7) located further from the ATV.

Electromagnetic fields radiated by the S-band antennas

As the ATV-ISS system orbits the Earth, its z-axis is normally Earth-oriented and its x-axis oriented along the trajectory. For the present study, therefore, it is interesting to simulate essentially the field radiated in the half-space characterised by $z < 0$, where the satellites to be linked with the ATV-ISS system are usually located. This is why, in the following figures, the UTD simulated results are only visualised in this half-space.

Figure 8 is a three-dimensional view of the co-polarised and cross-polarised components radiated by the quadrifilar helix antenna mounted on the ATV docked on the ISS, for the case with horizontal solar panels (panels located in the x-y plane). The vertical scale denotes the directivity, and the horizontal scale denotes the angle θ measured from the (–z) axis; the circular scale denotes the angle ϕ measured from the x-axis in the direction of the y-axis. A circle at $\theta = 70°$ has been superimposed to indicate the angular region in which the ATV antennas have usually to guarantee coverage.

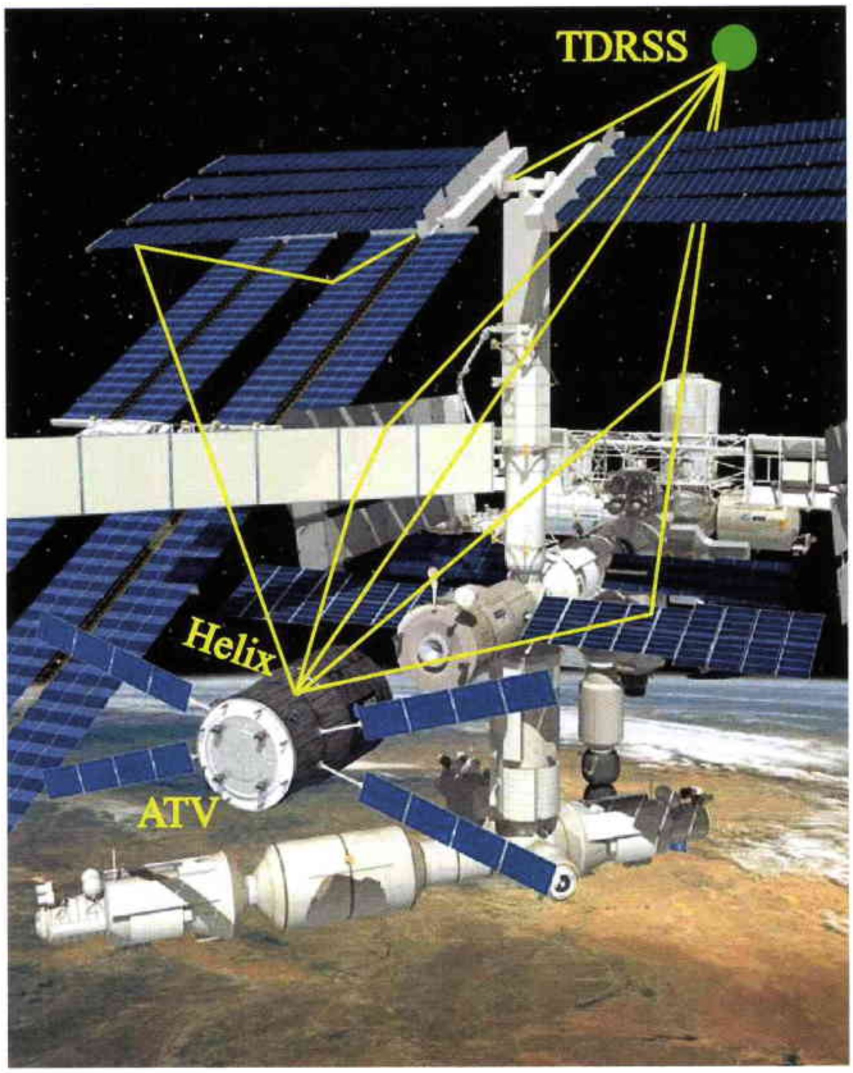

Figure 7. Some possible ray contributions in the link between the ATV and TDRSS

For the co-polarised component (on the left), the blue zones represent the region shadowed by the ISS. In particular, the blue horizontal area indicated by the number 1, represents the shadow of the Russian mast supporting the Russian solar panels. The vertical light-blue area, indicated by the number 2, represents the shadow of the Russian solar panels, while the blue curved area indicated by the number 3 represents the shadow of the vertical thermal radiator attached to the Russian mast. In this particular case, with all solar panels perpendicular to the z-axis, the large American solar panels slightly modify the pattern of the helix antenna. Their shadow is evident only near the border of the circle, i.e. for θ near 90°. Observing the cross-polarised component (right), one can see that it is larger than the corresponding free-space component and that this image is relatively noisy. It is interesting to note that the red area, indicated by the number

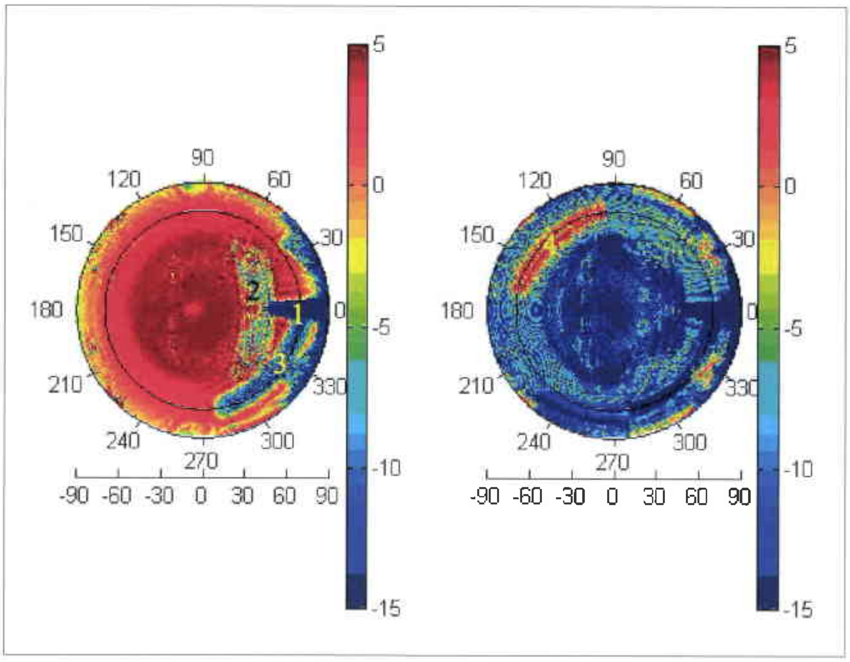

Figure 8. Representation of the co-polarised (left) and cross-polarised (right) radiation from the helix antenna mounted on the ATV docked on the ISS, with solar panels horizontal

4, is due to the reflection on the vertical thermal radiator. This reflection contribution is particularly evident in the cross-polarised component.

Figure 8 shows that the Russian mast, the vertical thermal radiator and the Russian solar panels create important scattering contributions in the radiated pattern. Despite the fact that these Russian appendages are smaller than the American ones, because of their position near the ATV and because they are located exactly in the half space where the TDRSS satellites are normally positioned, their structures will always modify the pattern of the helix antennas.

Figure 9 shows the same quantities as plotted in Figure 8, but for the case when the solar panels are vertical (located in the plane y-z). One can see that in this case the American solar panels generate significant scattering contributions. For the cross-polarised components, the comments regarding the previous figure remain valid.

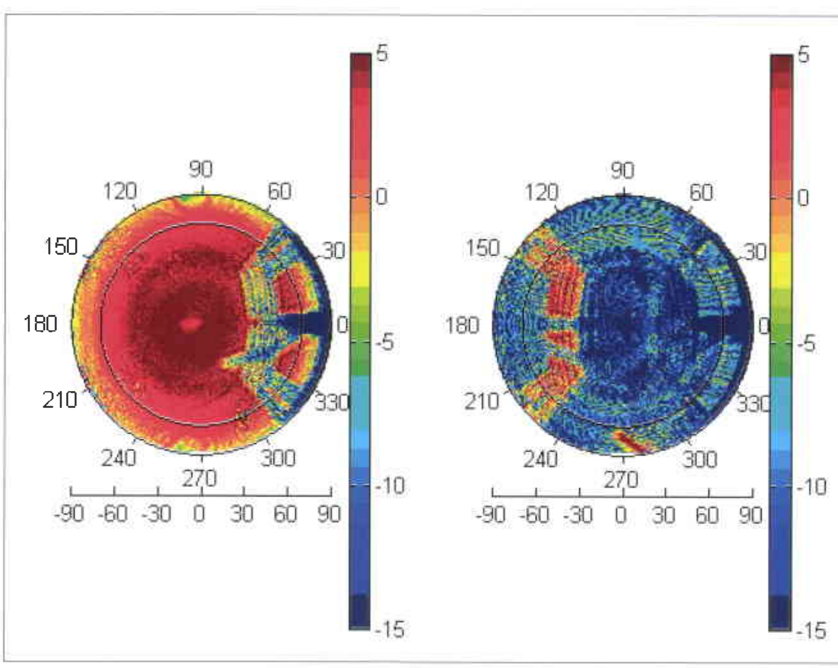

Figure 9. Representation of the co-polarised (left) and cross-polarised (right) radiation from the helix antenna mounted on the ATV docked to the ISS, with solar panels vertical

Electromagnetic fields received by the TDRSS satellites

Once a good electromagnetic modelling tool has been established, the electromagnetic field received by the three geostationary TDRSS satellites can be estimated, based on the following steps:

- The Sun's trajectory with respect to the ATV-ISS system was studied.
- The trajectories of the TDRSS satellites with respect to the ATV-ISS system were analysed.
- Some critical cases were selected and the signal arriving at the TDRSS satellites estimated and compared with that reaching the satellites when neglecting the ISS effects.
- Due to the difficulties of obtaining other reference data, a simple Geometrical Optics (GO) simulator to evaluate the shadowing effects associated with the main appendages of the ISS for every trajectory was also implemented. Its results were in good agreement with those obtained with the more rigorous simulator introduced previously. This test provided a cross-check on the simulator's accuracy.
- An estimation of the time available to establish the ATV-TDRSS connection was finally obtained.

During every Earth orbit, the ATV establishes a link with every TDRSS satellite, one after the other. However, in every instance the link could be established with two of them. To choose the best satellite, the angle between the helix-antenna axis and the direction to every satellite is continuously evaluated and the satellite associated with the minimum angle selected to maintain the strongest radiated antenna signal. This is essentially the same procedure followed by the S-band antennas to track the TDRSS satellite. Several cases have been analysed and the conditions under which the appendages of the ISS particularly disturb the link ATV-TDRSS have been identified.

First of all, the trajectories of the three TDRSS satellites with respect to the ATV-ISS composite have been studied. An interesting and important property of the trajectories of the three satellites has been evidenced. When a TDRSS satellite trajectory is projected on the two-dimensional colour plot representing the pattern of the S-band antennas in z < 0 half-space (Fig. 10), one obtains an arc.

This type of visualisation is very useful for identifying the most critical trajectories before performing the complete electromagnetic analysis. The worst trajectories are those that intersect more the blue areas representing the shadow regions. The blue areas are the regions where the radiation from the ATV antennas, blocked by the presence of the ISS, does not ensure an electromagnetic coverage towards the data relay satellites.

In Figure 10, the electromagnetic field represented has been obtained by only including the geometrical shadowing effects due to the ISS: these are the dominant effects in the co-polarised component. The three trajectories relate to the three TDRSS satellites. In particular, the yellow curve refers to satellite number 1, the green curve to satellite number 2, and the magenta curve to satellite number 3. The geostationary orbits of these three satellites are characterised by three fixed angles with respect to the Greenwich meridian: 41°W, 174°W and 275°W.

In Figure 10, the three trajectories cross the blue shadowed regions, with a corresponding reduction in signal intensities. This graphical analysis is useful, but it is important to remember that the orientation of the panels continuously changes to track the Sun, and that the blue shadow is only relevant to one possible orientation. When varying the orientation of the panels, the blue shadow regions change but they are always located in the right-hand part of the plot.

The positions of the trajectories depend on several factors: the date, the hour and a certain angle Ω_0 defining the angular distance, along the equator, between the starting point of the ISS trajectory and the γ point (defined with respect to the Aries constellation). Once these time and geometrical parameters have been defined, the trajectory can be exactly positioned with respect to both the Sun and the TDRSS satellites.

The most critical trajectories have been plotted in Figure 10. One projected trajectory is exactly parallel to the 0° azimuth direction. This is the case in which the fixed part of the ISS and, in particular, the Russian mast, is shadowing one TDRSS satellite. The other two satellites remain possible targets for the shadow relevant to the moving solar panels. Physically, this condition only occurs in the particular case in which the ISS, crossing the equator, is linked with a TDRSS satellite with exactly the same longitude as the crossing point. Starting from the knowledge of all the geometrical and temporal parameters, the link between the ATV-ISS system and the TDRSS satellites has been studied. A detailed analysis of the electromagnetic results relevant to the conditions shown in the Figure 10 is presented below.

In Figure 11 the case corresponding to Figure 10 is analysed. The abscissa θ represents the orbit angle, the so-called 'true anomaly', ranging from 0° to 360°. The angular range corresponds to an entire orbit of the ISS around the Earth. Figure 11a shows which TDRSS satellite is linked to the Space Station during a particular orbit. In these figures, the background colours denote the TDRSS satellite linked at each particular moment to the Station: yellow refers to TDRSS satellite number 1, green to satellite number 2, and magenta to satellite number 3.

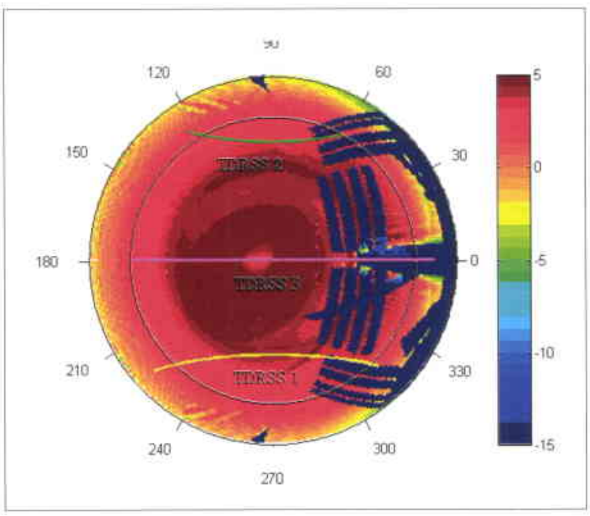

Figure 10. Radiation of the ATV helix antenna towards the relay satellites, showing the shadow of the ISS. Possible data-relay-satellite trajectories are shown

In Figure 11b, the co-polarised component of the field radiated from the ATV-ISS system, evaluated exactly at the TDRSS position, is plotted with respect to the corresponding component obtained by only considering the ATV in the absence of the ISS. Figure 11c is relevant to the cross-polarised components, where the signals are less strong but present a larger dynamic range. Figure 11d represents the occurrence along the same trajectory of geometrical shadowing effects due to the American solar panels, the Russian solar panels, the Russian mast supporting the Russian panels, and the SPP thermal radiator. The ordinate value 0 denotes no shadowing effect; the value 1 indicates that shadowing occurs. Some agreement exists between this elementary Geometrical Optics model and the rigorous results plotted in Figure 11b. All data have been obtained using one point every 5°, which is equivalent to sampling the signal every 1 min and 15 sec.

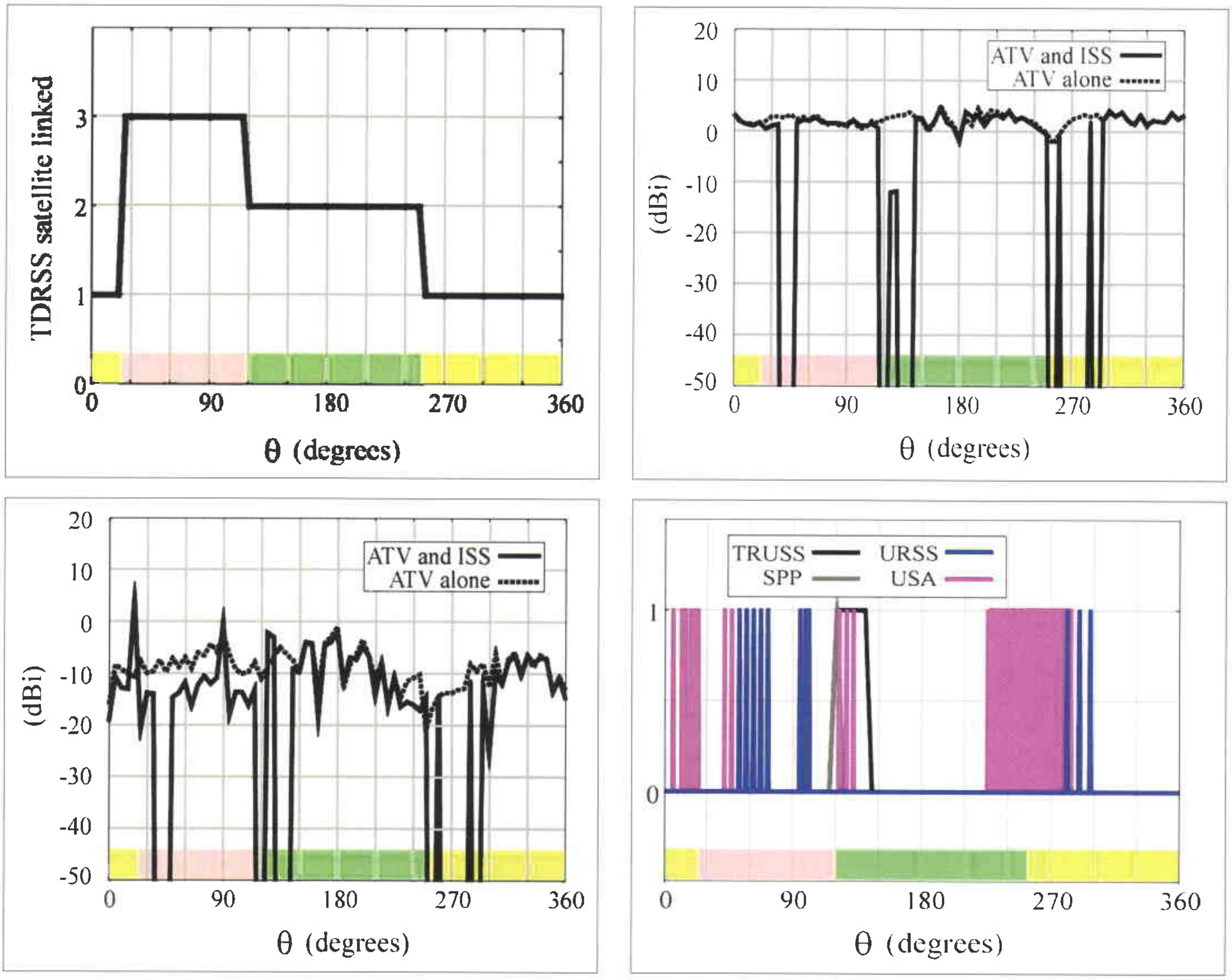

Figure 11. Detailed analysis of the ATV-TDRSS link - the worst-case scenarios for:
(a) TDRSS satellites linked to ISS in one orbit
(b) Co-polarised signal at TDRSS with and without ISS
(c) Cross-polarised signal at TDRSS with and without ISS
(d) Elements of ISS shadowing the ATV-TDRSS link

Figure 11, which represents one of the worst-case scenarios, shows that around 3/4 of the entire trajectory can be considered safe to establish the link: this means that some 67 minutes are available for the link, and only 23 cannot be used. It can be seen in the previous figures that the direct link is interrupted at least three times during every ISS orbit. Hence, at least 22 minutes of link time are always available, which is more than twice the 10 minutes required. This confirmation represents the main result of our study.

Conclusions

Our study has demonstrated that for every orbit of the ATV-ISS system, there will be sufficient margins to establish a direct link with the TDRSS satellites. Some 67 minutes per orbit can be used to establish the ATV-TDRSS link and at least 22 minutes are available for a continuous link.

Compared to the previously available electromagnetic simulators, the tool that has been developed is much more accurate because of the better geometrical description of the ATV-ISS system, because of the higher-order interaction effects considered in the analysis, and because the position of the Sun and the TDRSS with respect to the orbiting ATV-ISS system has been carefully taken into account. The new electromagnetic simulator can also be used to study the rendezvous phase in which the ATV is approaching the ISS and the link between the ATV and the Global Positioning System (GPS) satellites. The new simulator can also be easily modified for analysing other electromagnetic links involving antennas working at different frequencies and located elsewhere on the ISS structure, and also for the design and positioning of those antennas.

Measuring Ocean Salinity with ESA's SMOS Mission

– Advancing the Science

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The Soil Moisture and Ocean Salinity (SMOS) mission is ESA's second Earth Explorer 'opportunity mission', scheduled for launch in early 2006. Selected for an extended feasibility (Phase-A) study in 1999, which was completed in December 2001, SMOS is currently in the design and development phase (Phase-B).

SMOS will exploit an innovative instrument designed as a two-dimensional interferometer for acquiring brightness temperatures at L-band (1.4 GHz) to retrieve soil moisture and ocean salinity. Both are key variables used in weather, climate and extreme-event forecasting. As a secondary objective, data acquired by SMOS over ice/snow regions may be used to characterise the ice and snow layers and thus complement other satellite observations to advance the science of the cryosphere*.

Introduction

Ocean-salinity observations from space have been identified as a high priority in the Integrated Global Observing Strategy-Partnership (IGOS-P) Ocean Theme Team Report (Lindstrom et al., 2001). The goal in observing ocean salinity is derived from the Global Ocean Data Assimilation Experiment (GODAE) requirements, which include global observation of ocean salinity with an accuracy of 0.1 practical salinity units (1 psu = 1 g salt in 1 kg of seawater), every 10 days at 200 km spatial resolution. This poses a challenge not only in the instrument's design, but also for the retrieval technique, including measurement corrections.

This article outlines ESA's science activities dedicated to advancing our knowledge of the ocean-salinity signal and it's dependence on sea-state condition, in order to develop and enhance retrieval techniques for the SMOS mission.

The ocean-salinity objectives

Knowledge of the distribution of salt in the global ocean and its annual and inter-annual variability are crucial in understanding the role of the ocean in the climate system. It is well known that ocean currents and air-sea heat fluxes are regulating our climate. The Gulf Stream, for instance, transports warm surface water from the Caribbean to Europe, which is the reason for the moderately mild winters in central and northern Europe. As the Gulf Stream flows north and northeastward, the surface water cools and becomes denser. Moreover, evaporation will simultaneously increase the surface salinity and hence further increase the density. As a result, the ocean surface layer will gradually reach a density such that stable stratification with the water below can no longer be maintained. It will then trigger convective overturning and form deep water. The corresponding overall basin-scale, three-dimensional oceanic flow is commonly known as the 'thermohaline circulation'. Sea-surface salinity is therefore one of the key variables for monitoring and modelling this global oceanic circulation pattern, which in itself is an important indicator for climate change.

Ocean-surface salinity is closely correlated with estimates of net Evaporation minus Precipitation (E-P). The E-P balance is difficult to measure accurately over the ocean by

* See also http://www.esa.int/livingplanet

conventional means, and so satellite-based maps of ocean salinity would provide a tool to constrain (E-P) estimations at global scale. It would provide insights into the phenomena driving the thermohaline circulation and allow better estimation of the latent heat flux. More accurate knowledge of the (E-P) balance would also improve the characterisation of the stratification of the surface layer of the ocean, and thereby improve estimates of the mixed-layer depth variation and its impact on the intensity of the surface currents.

The scientific objectives for observing ocean salinity with the SMOS mission are to:
– *Improve seasonal to inter-annual (ENSO) climate predictions:* Effective use of ocean-salinity data to initialise and improve the coupled climate-forecast models, and to study and model the role of fresh-water flux in the formation and maintenance of barrier-layer and mixed-layer heat budgets in the tropics.
– *Improve the estimates of the ocean rainfall and thus the global hydrologic budgets:* The 'ocean rain gauge' concept shows considerable promise in reducing uncertainties in the surface freshwater flux on climate time scales, given ocean-salinity observations, surface velocities and adequate mixed-layer modelling.
– *Monitor large-scale salinity events:* This may include ice melt, major river run-off events, or monsoons. In particular, tracking inter-annual ocean-salinity variations in the Nordic Seas is vital to long-time-scale climate prediction and modelling.
– *Improve monitoring of sea-surface salinity variability:* This is needed in order to better understand and characterise the distribution of bio-geochemical parameters in the ocean's surface.

The Global Ocean Data Assimilation Experiment (GODAE), a pilot experiment set up by the Ocean Observations Panel for Climate, which aims to demonstrate the feasibility and practicality of real-time global ocean modelling and assimilation systems, proposed an accuracy requirement for satellite salinity for global ocean-circulation studies of 0.1 psu for averages over 10-day time intervals in 200 km x 200 km boxes.

Considering the exploratory nature of SMOS, the GODAE open-ocean requirement represents a valid scientific goal, but is nevertheless a serious technical challenge. The image reconstruction errors, their correlation characteristics, the calibration stability, and the uncertainty related to the contribution of the surface characteristics of the signal may only allow salinity to be retrieved with lower accuracy, particularly at higher latitudes. This has to be carefully addressed with the continued development of the SMOS demonstrator and numerical simulator to analyse the SMOS ocean-retrieval accuracy. It should furthermore be emphasised that lower temporal resolution, e.g. monthly aggregated products, would be sufficient for many climate studies, and may offer improved accuracy. Lower salinity accuracy, and thus higher spatial or temporal resolution (typically 0.5 psu, 50 km, 3 days) would provide the means to monitor moving salinity fronts in various regions.

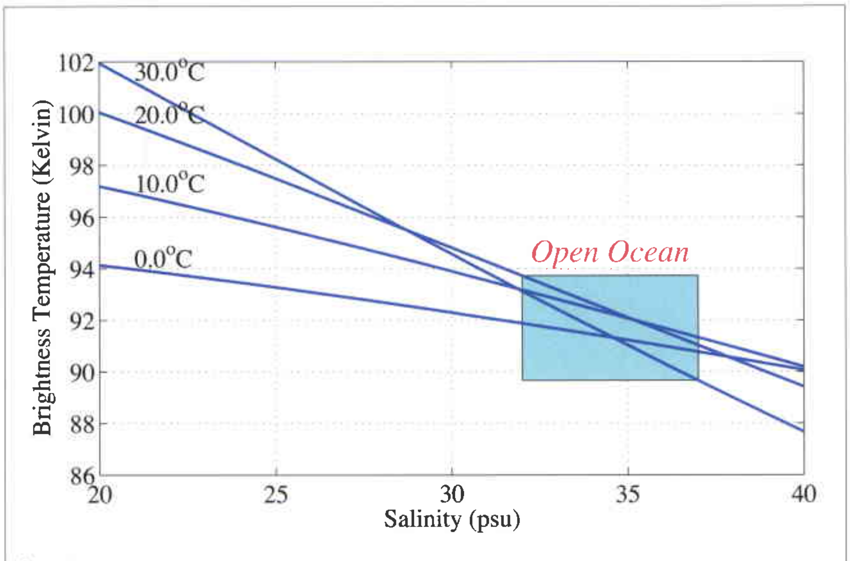
Signal sensitivity and perturbing factors

The dielectric constant for seawater is influenced, among other variables, by salinity. It is therefore possible to estimate sea-surface salinity from passive microwave observations, as long as other variables influencing the brightness-temperature (T_b) signal can be accounted for. These include Sea-Surface Temperature (SST), surface roughness, foam coverage, sun glint, rainfall, ionospheric effects and galactic/cosmic background radiation. Estimates have previously been made of the uncertainties associated with some of these perturbing factors.

The sensitivity of the brightness temperature to ocean salinity is a maximum at low microwave frequencies and the best conditions for salinity retrieval are found at L-band (1.4 GHz). However, it must be stressed that even at this frequency the sensitivity of the brightness temperature to salinity is low (at nadir 0.75 K per psu for an SST of 30°C, decreasing to 0.5 K per psu at 20°C, and 0.25 K per psu at 0°C), placing demanding requirements on the performance of the instrument (Figs. 1a,b). Additional information for constraining the retrievals is provided by the multi-angular viewing and the polarisation.

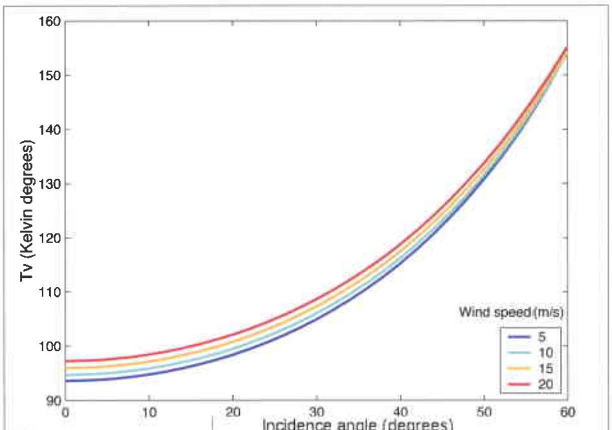
Since the radiometric sensitivity is low, it is clear that ocean salinity cannot be estimated with the required accuracy from a single pass. However, if the errors contributing to the uncertainty in brightness temperature are random, the necessary accuracy can be obtained by aggregating the individual SMOS measurements in both space and time. In the following, this combination of measurements made at various incidence angles and various times will be referred as an 'averaging procedure', although the way in which the measurements will be combined needs to be thoroughly studied. The averaging procedure calls for excellent stability (0.02 K/day) from the radiometer.

The ocean-salinity retrieval from L-band radiometric measurements implies the use of ancillary data sources, for wind and SST in particular. As the ancillary data will not be recorded simultaneously with SMOS, the averaging procedure will allow use of data acquired (or analysed) at different times within the average window. The effects of the spatial and temporal variabilities of these data on the ocean-salinity retrieval have to be analysed.



1a

Figure 1a. Variation in brightness temperature due to sea-surface salinity at L-band as a function of SST for nadir observations (from Lagerloef et al., 1995)



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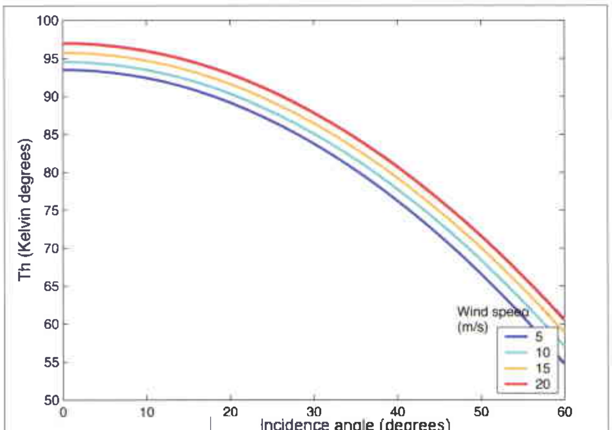


1b

Figure 1b. T_v and T_h as a function of incidence angle for various wind speeds (5, 10, 15 and 20m/s) as simulated by a two-scale model at 35 psu and 15°C, without foam effect (from Dinnat et al., 2002; Yueh, 1997)

Scientific support studies

The analysis, enhancement and validation of models accounting for signal-perturbing effects such as wind (azimuthal dependence, roughness and foam), sea-surface temperatures, rain, Faraday rotation and the timeliness of collocated observations, needed to be addressed by scientific support studies. In addition, appropriate campaigns had to be organised and conducted to provide suitable data. Once elaborated, the enhanced retrieval schemes, together with the system error budget, a vicarious calibration scheme, and a final-product definition will provide insight into the expected usefulness of SMOS data for the ocean-salinity objectives via dedicated impact-assessment studies. The following paragraphs briefly outline the activities initiated by ESA during the Phase-A study and the preliminary results therefrom.

The Ocean Salinity Requirement Study

A study addressing the requirements for a future space-borne mission to observe sea-surface salinity was kicked-off in September 2000 and was completed in April 2002. The study was managed by NERSC of Norway as prime contractor, and involved a consortium of 10 institutes within Europe. The main objectives were a scientific-observation requirements analysis and impact assessment for ocean-atmosphere and thermohaline circulation models using different salinity accuracies, and more specifically to:

- examine and quantify the effects of surface-roughness changes, presence of foam, precipitation, and diurnal sea surface temperature variations on sea surface emissivity and derive the resulting Sea-Surface Salinity (SSS) retrieval accuracy over incidence angles ranging from nadir to 50°
- examine and quantify the impact of the SSS measurements with the above accuracy on ocean (and coupled ocean-atmosphere) modelling for different regions characterised by cold surface water, fresh-water input from rivers, melting sea ice and ice sheets, and evaporation minus precipitation, as well as in regions with limited temporal and spatial changes in surface salinity.

State-of-the art ocean-circulation models were used to provide a first qualitative assessment of the expected salinity signal. Three different models were applied to characterise typical SSS variations for different oceanic regions:

- the Océan PArallélisé (OPA) global ocean model, from LODYC, Paris, focusing on the Indian Ocean

- the CLIPPER model developed for the Atlantic Ocean, and
- the Miami Isopycnic Coordinate Ocean Model (MICOM) model, adopted by the NERSC team focussing on the Northeast Atlantic and Nordic Seas.

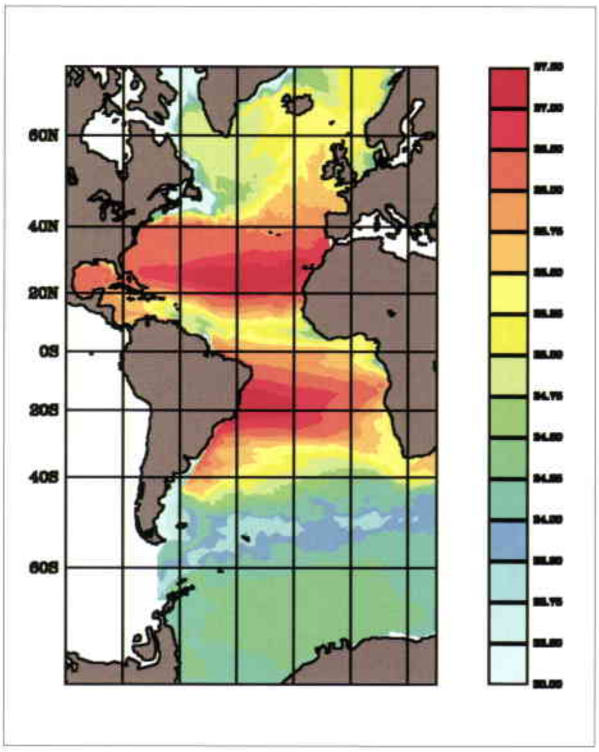
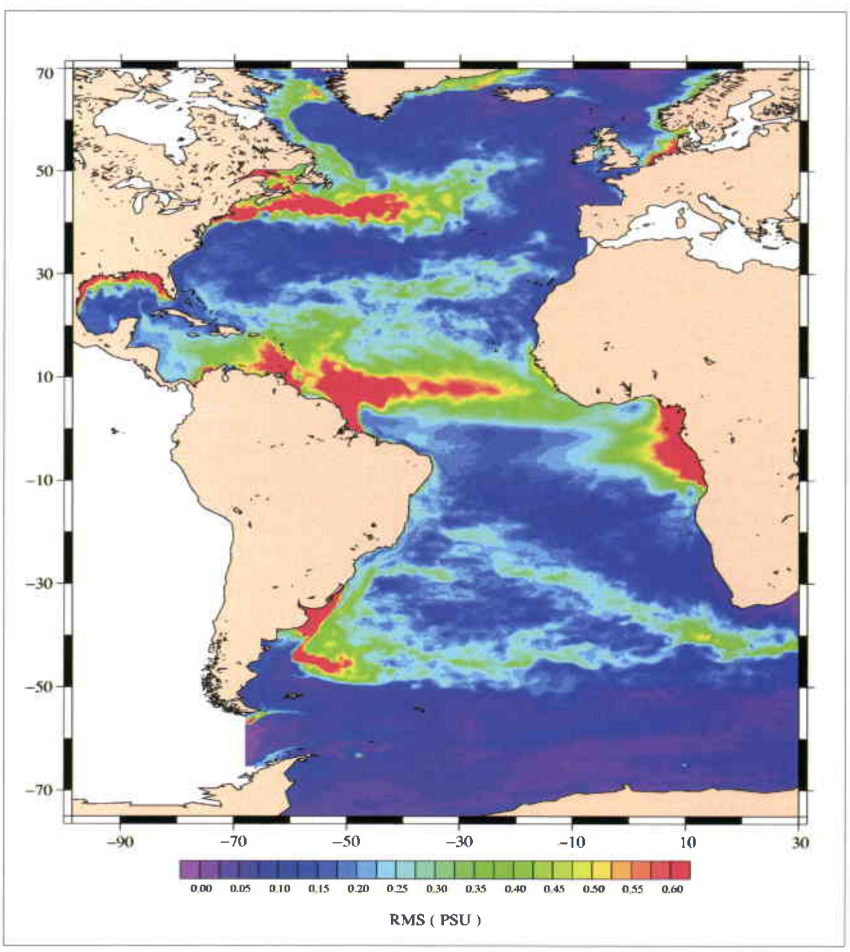


Figure 2. Simulated Sea Surface Salinity (SSS) distribution in the Atlantic using the Clipper model (mean SSS over the period 1997-1999). The model has not been adjusted for climatological values, resulting in higher SSS values for certain regions. However, a non-adjusted simulation provides a more realistic distribution of SSS variations

Figure 3. Expected Sea Surface Salinity (SSS) variations over a period of three years (five-day mean values from daily Clipper simulations, 1997-1999)



Using these model simulations, a variety of dynamic features like boundary currents (Gulf Stream, Benguela Current), tropical regions with high fresh-water exchange due to precipitation and river discharges were analysed. Characteristic salinity patterns and their temporal and spatial variations have been derived. The typical example shown in Figures 2 and 3 is for the Atlantic Ocean.

Salinity variations are in the range of 0.05 to 0.5 psu. Assuming the GODAE requirements could be met, most interesting salinity features would be detectable. However, these simulations show that also with reduced spatial resolution, seasonal features will be observed with much better accuracy than the present knowledge of global seasonal Sea Surface Salinity (SSS) variations. Significant improvements can be expected from SMOS for mesoscale features in the 200–300 km range. These features occur in tropical regions and involve strong salinity variations of up to 2 psu.

To study the sensitivity of brightness temperature (T_b) to wind velocity, SST and SSS, the UCL and Yueh-LODYC two-scale emissivity models were used. The impacts of different parameterisations for the modelling of the sea surface (sea-water permittivity, wave spectrum, foam coverage) and for the modelling of electromagnetic scattering in each of these models were analysed. The results are summarised in Table 1.

Table 1. Influence of various sea-surface parameters on brightness temperature (T_b) for various parameterisations in two-scale Yueh-LODYC and UCL models

δTb/δSSS (K/psu)	0.7 at 30°C to 0.25 at 0°C ~1 K bias : Ellison > Klein & Swift
δTb/δSST (K/°C)	0 at 15°C to 0.13 at 30°C
δTb/δ (K/m/s)	Without foam, at nadir : 0. to 0.24 K/m/s
Upwind-downwind asymmetry	For _< 30° U < 15 m s^{-1} , less than ±0.1K At = 50° U = 15 m/s, ±0.1 K/m/s to ±0.4K/m/s depending on wave spectrum
Upwind-crosswind asymmetry	< ± 0.1K to ± 0.4 K depending on wave spectrum
Foam effect	< 0.1K below 7 m/s for U >10 m/s several K differences between various parameterisations

The results show that there is a need to improve the modelling of the surface-roughness effect and the foam effect, both effects being modelled with an uncertainty larger than 1 K for commonly encountered oceanic situations. Modelling of the permittivity is also critical.

New models for the foam emissivity and coverage have been developed within the study, which still need to be validated. Preliminary results indicate a relatively small foam emissivity at L-band for wind speeds lower than 12 m/s. Comparisons between T_b simulated with the UCL and Yueh-LODYC emissivity models and WISE 2000 measurements (see below) indicate a better agreement of models that predict a higher sensitivities of T_b to the wind speed. It should be noted, however, that possible disturbances of the wind/wave field due to the platform and due to limited fetch have not been accounted for. In further studies, such effects would need to be accounted for before extrapolating these conclusions to a model run in open-ocean conditions. A more complete set of measurements describing the sea state has been acquired during the WISE 2001 campaign, which should help in interpreting the L-band measurements.

Moreover, further campaigns are needed in the open ocean to validate these results, which were obtained in a limited fetch area. In this respect, the EuroSTARRS measurements made in the Atlantic Ocean (Gulf of Gascogne) in November 2001 are very useful.

The impact of the sea-surface temperature diurnal cycle was also investigated, using the cool-skin and warm-layer model of Fairall et al. Under realistic wind-speed and SST conditions, non-negligible effects appear in some parts of the ocean during the evening orbit: the SST diurnal variation averaged over 10 days may reach 1.5°C in regions of very low wind speed, leading to SSS biases of up to 0.4 psu. Therefore, when dealing with SMOS measurements made during evening orbits, it will be necessary to correct for this effect.

The impact of rain at 1.4 GHz on the brightness temperatures at satellite altitude was also investigated. It might be important because of its high variability compared to the sensitivity of brightness temperature to changes in surface salinity. The Mie scattering calculations show that at 1.4 GHz only the extinction of water seems to be important. The extinction for water and ice is two orders of magnitude smaller than at 10.7 GHz. For an assumed rain rate of ~9 mm/h and a rain-layer thickness of ~8 km, the maximum atmospheric contributions occur at 50 deg incidence angle with a signal contribution of 4.2% and 7.1% for the upward emission, and 4.5% and 10.4% for the reflected downward emission with vertical and horizontal polarisations, respectively (values given as a percentage of the total signal at satellite altitude). The rain effect causes a bias in the brightness temperature that is almost independent of all surface parameters. Integration over the different SMOS footprint sizes will minimise this effect, especially in the case of inhomogeneous beam filling. However, it should be included in forward radiative-transport calculations.

A first estimate of the salinity retrieval error linked to noise on brightness temperature measured in the SMOS configuration, and to noise on ancillary parameters (wind and SST), was made. Using a retrieval of sea-surface salinity at each satellite pass to account for wind variability from one pass to another, the error on the SSS averaged over 10 days and 200 km was estimated to be less than 0.1 psu. For this preliminary estimate, errors due to image reconstruction were neglected and it was assumed that all errors are uncorrelated. Further studies are needed to investigate the consequences of these hypotheses.

The Ocean Salinity Retrieval Study

The ocean-salinity retrieval study is designed to advance the understanding of the physics of the SMOS characteristics (L-band, range of incidence angle, dual polarisation) for different sea-state conditions, and to develop retrieval algorithms for ocean salinity from SMOS observations, accounting for the spatial resolution (varying footprints), mixed pixels due to wind variability, foam, as well as the timeliness and accuracy of ancillary data. The prime contractor is CLS of France. The activity, which was started in July 2001 and will last for one year, embraces the following tasks:

- Extension of the modelling exercise of the previous study.
- Validation of the models developed.
- Improvement of models accounting for SMOS characteristics (footprint, auxiliary data).
- Analysis of standard retrieval techniques.
- First steps towards an assimilation scheme – improved retrieval techniques.

The electromagnetic part of the new emission model uses the recently developed Small Slope Approximation (SSA), at second and third order. This yields the first three harmonics of the brightness temperatures for the four Stokes parameters. For the background of surface waves with small slopes, the spectral model of

Kudryatsev et al. is used. Reduced bi-spectrum and hydrodynamic modulation transfer functions follow the models of Yueh and the hydrodynamic theory of Elfouhaily et al. The locally distributed breaking events are described by using the slope probability density function as introduced by Chapron et al. Ensemble averages are computed using a new foam coverage model. Outputs from this complete emissivity model have been compared to those from other available models and to experimental measurements made at higher frequencies. Comparisons for a few typical salinity, wind-speed and temperature conditions show relatively good agreement.

Sensitivity of the modelled brightness temperatures to the surface wind speed for different incidence angles has been compared to the WISE measurements (see below) as well as to previous observations made at L-band. Sensitivities obtained with the SSA model are mostly (H and V polarisations, incidence angles between 25° and 65°) in very good agreement with the WISE and Hollinger measurements. Absolute validation of the brightness temperatures has been performed. The simulated brightness temperatures for V polarisation are consistent with measured L-band radiometric measurements. For H polarization, a bias of 3 K appears, but this has to be carefully considered due to the very few measurements made in this polarisation.

Figure 4. The Casablanca oil rig

The critical part of the validation is that of the sub-models (surface spectrum and foam coverage). Validation of the models used to describe the surface topography has not been possible yet. The foam-coverage model used in the SSA model has nevertheless been validated using video-camera data, which is in very good agreement with other empirical models.

ESA's SMOS campaigns

In order to analyse signal dependence and to validate existing and improved models, three campaigns were conducted during the Phase-A study: the WInd and Salinity Experiment (WISE), the L-band Ocean Salinity Campaign (LOSAC), and the EuroSTARRS Campaign.

WISE

The WISE campaign was conducted in 2000 and 2001 from an oil rig (Casablanca Tower) about 50 km off the coast of Tarragona, in the northwest Mediterranean (Fig. 4). The overall objective was to measure and analyse polarimetric L-band emission under varying incidence and azimuthal viewing angles for a wide range of sea-state conditions. The LAURA L-band radiometer of the Polytechnic University of Catalonia (UPC), Spain, at the same time prime contractor and responsible for all logistics, was used as the core instrument (Fig. 5). In addition, a polarimetric Ka-band radiometer, a video system (for foam estimation), an infrared radiometer (for SST estimation) and a stereo-camera (for sea-surface topography estimation), as well as four oceanographic and meteorological buoys, were deployed. Systematic measurements were acquired from 16 November to 18 December 2000, and from 9 to 15 January 2001. The experiment was repeated from 23 October to 22 November 2001, to cover stronger winds and avoid interferences (RFI problems) encountered during the first campaign, which probably originated from airport radar systems. Data were recorded for wind speeds higher than 50 knots (~100 km/h), during one of the most severe storms this region ever had (Fig. 6). In addition, this experiment was coordinated with the EuroSTARRS (see below) campaign, which enabled contemporaneous data acquisition during an overflight of the STARRS instrument. These data are still being analysed, but the first preliminary results are presented below.

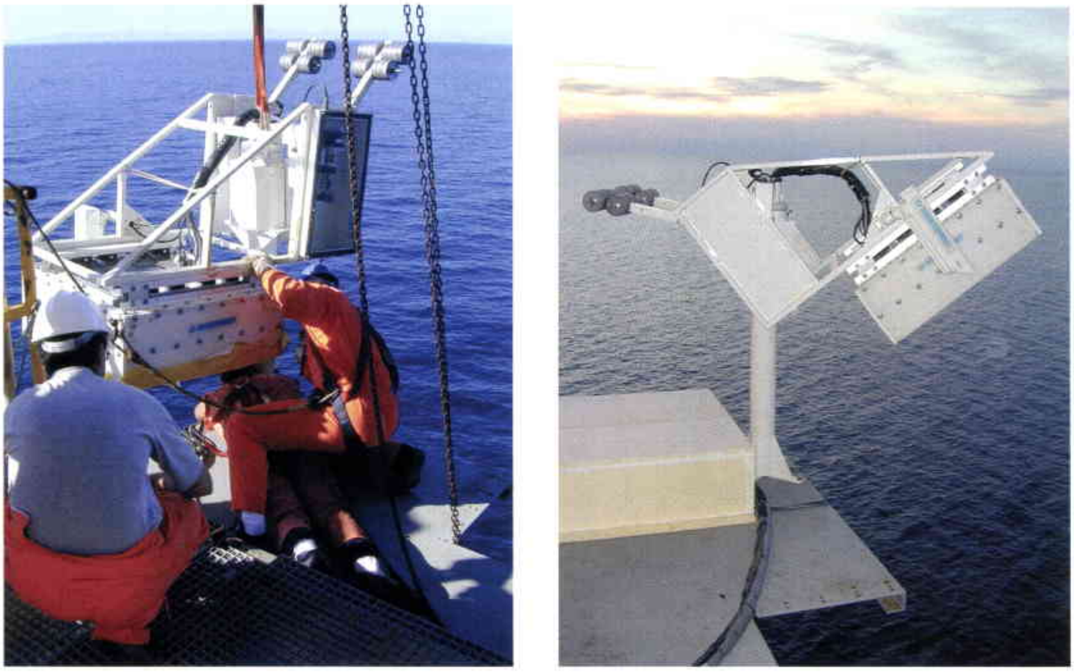


Figure 5a. LAURA during its installation on the Casablanca oil rig, 32 m above the sea surface, and during measurement taking on a calm day

The brightness temperatures' sensitivities to wind speed derived from WISE-2000 data confirm existing experimental data and are in agreement with numerical results predicted by the Yueh-LODYC two-scale model emissivity using the Durden and Vesecky (1985) sea spectrum multiplied by a factor of two. The experimental results show a sensitivity that, extrapolated at nadir, is about 0.22 K/(m/s), increasing with incidence angle for horizontal polarisation, and decreasing with incidence angle for vertical polarisation, being zero around 55° – 60°. The azimuthal variation is small, being approximately 0.1 – 0.2 K at low-to-moderate wind speeds, but up to 3 – 4 K peak-to-peak variations were measured during the night of 10 November 2001, a situation similar to that shown in Figures 6, with lower wind speed but greater significant wave heights (>11 m). WISE 2001 data is being analysed to improve the determination of the radiometric sensitivities to wind speed (notably via surface roughness and foam coverage), mainly at large incidence angles.

These results have been applied to a performance study of a SMOS-oriented sea-surface salinity retrieval algorithm. To avoid geometrical and Faraday-rotation polarisation mixing, the algorithm is based on minimisation of the error between the sums of the measured and the modelled T_h and T_v, for different pixel tracks in the alias-free field of view. Except for low sea-surface salinities and temperatures, the retrieved salinities have a root-mean-square error of approximately 1 psu for one satellite passage. Further research will focus on possible error reduction using several satellite passages within a 10 to 30 day interval, on the assumption that the error contributions from individual pixels are random.

LOSAC

The LOSAC campaign was initiated to address azimuthal dependence of the first two Stokes parameters ($T_{b,v}$ and $T_{b,h}$) on wind speed and direction, which is not yet fully understood. The EMIRAD full-polarimetric L-band radiometer was exploited aboard a C130 aircraft operated

Figure 6. Rough seas during the storm on 15 November 2001, when the wind speed recorded by the platform's meteorological station 70 m above the sea surface exceeded 76 knots

by the Royal Danish Air Force over the North Sea. The instrument is owned by the Technical University of Denmark (TUD), which acted as prime contractor for this experiment.

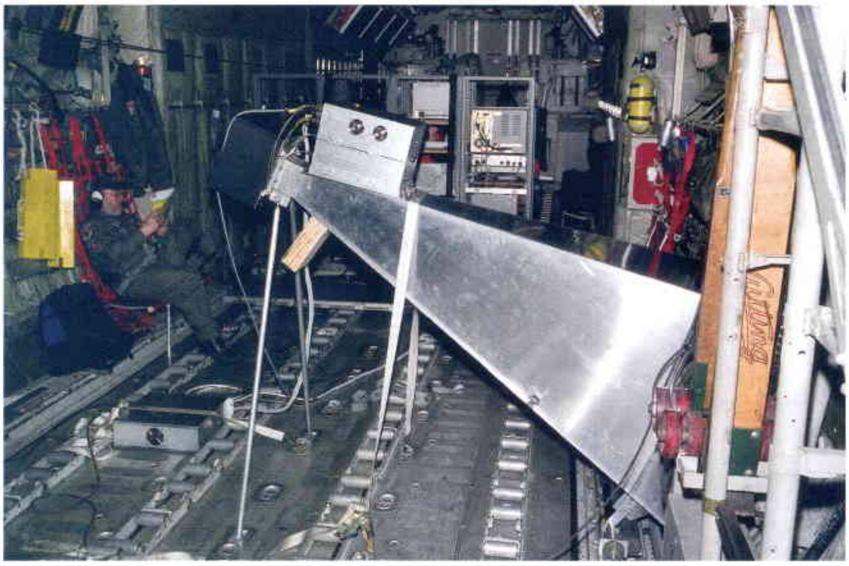


Figure 7. EMIRAD aboard the Hercules C130 aircraft

EMIRAD's large antenna horn looked out through the starboard parachute door (Fig. 7), an optimised installation for investigating azimuthal signatures by flying circuits with the antenna pointing at the sea surface. By changing the roll angle of the aircraft and thus the diameter of the circle of flight, data could be acquired for different antenna-beam incidence angles. A first technical test flight carried out on 16 January 2001 revealed technical problems due to RFI, which could be solved by additional shielding. Three science flights were subsequently conducted over the North Sea, on 15 and 23 March and 25 October. Additional flights are planned over the North Sea, and possibly over the North Atlantic.

Preliminary data analysis indicates a rather unstable situation regarding azimuthal signatures. In most cases there is no clear signal, but in some cases we observe that during a sequence of equal circuits, a clear azimuth signal can be present on one or even two circuits, yet disappears on the third. Figure 8 shows the corresponding result when the azimuthal signal is present. This example shows a clear 1 K peak-to-peak signal, but on the next circuit it has gone.

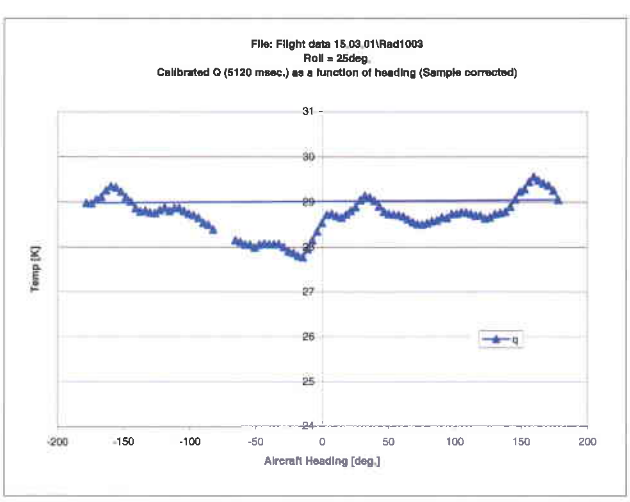


Figure 8. Second Stokes parameter as a function of aircraft heading (uncalibrated)

The L-band response to waves is poorly understood (L-band wavelengths are too long for capillary waves, yet too short for normal gravity waves), but it has been suggested that trains or packets of swell travelling in and out of the radiometer footprint may be responsible for the behaviour. In that case, it will never have any influence on SMOS, bearing in mind its 50 km footprint integrating over huge areas compared to an airborne system which typically has a 500 m footprint. Further analysis is ongoing.

EuroSTARRS

The main objective of the first exploitation of the Salinity Temperature and Roughness Remote Scanner (STARRS) in Europe (EuroSTARRS 2001) was to acquire SMOS-like observations for addressing a range of critical issues relevant to the soil-moisture objectives of the SMOS mission. Additional flights could be booked for ocean-salinity experiments and were coordinated with on-going campaign activities. The STARRS is owned by NRL (USA) and was operated during the campaign aboard a Dornier 228 by DLR, Oberpfaffenhofen (Germany). The instrument, a push-broom scanner with six beams, was mounted perpendicular to the flight direction and tilted to one side by 12° (Fig. 9). By overlapping flight patterns and accounting for the incidence angles of the different antenna beams, multi-angular observations up to 50° could be obtained. This required almost perfect flight navigation, which was supported by a new navigation system within the DLR aircraft.

Two flight paths were flown to support the ocean-salinity community: one along the shoreline from Bordeaux to the mouth of the Gironde river and outbound towards the Gascogne meteorological buoy located in the middle of the Bay of Biscay, and another from Barcelona to the Casablanca Tower. Circular flights with bank angles of 22° were performed over the Gascogne buoy and Casablanca Tower. Synoptic, along-track in-situ salinity and sea-surface-temperature measurements were acquired from research vessels operating at the same time. Both flights were made at sunset to avoid sun glint and took place on 17 and 21 November.

The first results are encouraging, although there are still some problems with the calibration of one antenna beam. Data analysis is currently ongoing.

Summary and outlook

Various science preparatory activities were initiated during the Phase-A studies to advance the science underlying the ocean-salinity objectives of the SMOS mission. The preliminary results can be summarised as follows:

Emissivity models: Uncertainties are introduced both by the complexity of the sea-surface structure, which depends mostly on wind speed, and by errors in the estimation of the dielectric constant at L-band. Models currently available simulate brightness temperature biased by up to 1.5 K. This bias varies with temperature and salinity. First results show a stronger confidence in the Klein and Swift model.

Wind speed – surface roughness: The change in emissivity due to the presence of sea-surface roughness is still poorly characterised, although it is large compared to the SSS signal: according to theoretical emissivity models, a 8 m/s wind speed changes Tb at nadir by 1 to 2 K, depending on the wave spectrum that is used. WISE 2000 measurements indicate that models and measurements do not disagree. Better constraints on emissivity models are expected from WISE 2001 and EuroSTARRS 2001 measurements.

Wind – azimuthal dependence: An azimuthal dependence on wind could not be confirmed for low wind speeds. This issue will be further investigated using the data acquired during WISE 2001, where measurements were made at high wind speeds.

Wind – foam: A physically-based foam coverage model has been developed within the Salinity Data Processing study. A foam model developed within the ocean-salinity requirement study showed that only thick foam (> 2 cm) contributes to the signal, but the signal level itself is still unknown. A foam experiment using a pond with a foam generator was proposed. The requirements for this experiment are currently being evaluated.

Sea-surface temperature: Sea-surface temperature should be available from complementary sensors with high accuracy (< 0.5 K). First study results show that diurnal variability is not critical, but needs to be corrected.

Faraday rotation: Various options (GPS measurements and TEC models, the use of the 1st Stokes, etc.) for correcting the Faraday rotation are considered. In addition, SMOS also provides a full-polarisation data-acquisition mode. Associated uncertainties and their impact on the retrieval accuracies still need to be analysed.

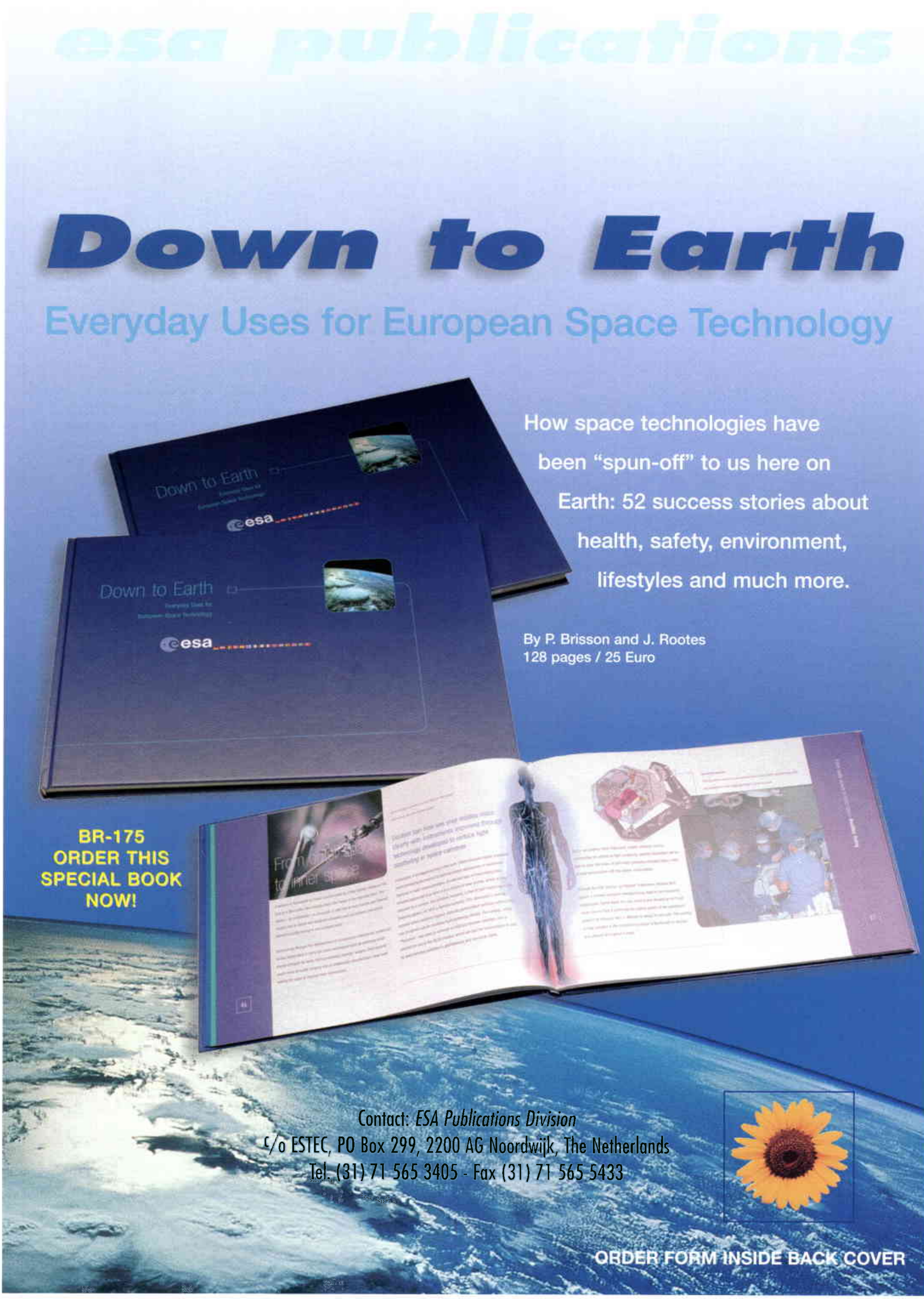
Figure 9. STARRS mounted on the DO228 aircraft in data-acquisition configuration (tilted). For take-off and landing, the instrument was moved into a horizontal position using a winding device specially designed for this campaign

Timeliness of auxiliary information: As mentioned above, diurnal sea-surface-temperature variations are not critical, but the accuracy and timeliness of wind measurements and the associated effects (wave spectra, sun glint, foam) are critical. More insights are expected from the ocean-salinity retrieval study.

The dedicated campaigns performed during the Phase-A studies have provided suitable data for further analysis, in which particular emphasis should be placed on the enhancement of wave spectra and foam models, their relationship to wind parameters, and the associated uncertainties. This is particularly important in order to estimate the accuracy that could be achieved by aggregating salinity observations over space and time. In addition, more focus needs to be given to system accuracy and stability, and a suitable vicarious calibration scheme using the fleet of buoys that should be operational by the time SMOS is in orbit.

Acknowledgement

The authors would like to express their gratitude to the study and campaign teams and to the SMOS Science Advisory Group for their invaluable contributions.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The MIRAS Demonstrator Pilot Project

– Towards SMOS

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Following several earlier feasibility studies, in 1998 ESA began the MIRAS Demonstrator Pilot Project within the Agency's Technology Research Programme (TRP) and General Support Technology Programme (GSTP) in an attempt to provide a technology solution to the inherent challenges of L-band radiometry. The objective was to build a representative element of the MIRAS instrument, which has subsequently been selected as the main payload for the Soil Moisture and Ocean Salinity (SMOS) mission. A second phase was initiated in April 2001 to demonstrate key end-to-end instrument performances, including antenna deployment and image validation, following approval of the SMOS mission Phase-A at the end of 1999.

Introduction

A first article about MIRAS was published in the November 1997 issue of the ESA Bulletin, in which we presented the results of the feasibility study of a two-dimensional aperture-synthesis radiometer for soil moisture and ocean salinity observations. In the meantime, the Soil Moisture and Ocean Salinity (SMOS) mission was selected in 1999 for Phase-A feasibility study as the second ESA Earth Explorer Opportunity Mission, carrying MIRAS as the sole payload on the Proteus platform. This article focuses on the technology achievements of MIRAS in the context of SMOS mission.

L-band radiometry faces the challenge of flying large apertures to achieve a spatial resolution suitable for scientific applications. Two-dimensional aperture synthesis is a solution to this challenge as it avoids mechanical scanning of a big reflector, and thus the technology research efforts of the Payload System Division at ESTEC have focused on this technique, more commonly known as 'interferometry'.

The MIRAS Demonstrator Pilot Project lumps a number of activities in various fields of expertise, to procure and test a representative part of the instrument. Some of the most relevant measurements obtained with the hardware so far are presented below, together with some of the early results of image validation tests using the first prototype MIRAS receivers and calibration methods. The instrument's evolution from the initial technology activities to its Phase-A configuration is also reviewed, and some insight is provided into the objectives and calendar for the SMOS mission itself.

MIRAS status prior to the Demonstrator Pilot Project

Figure 1 shows the MIRAS instrument as it looked back in 1997, following a major feasibility study for a large platform, a number of theoretical and breadboarding activities, and a down-sizing exercise onto a small platform, all conducted during the preceding four years. There was an array of three co-planar 5.2 m-long arms, with 27 radiating elements per arm with a spacing of 0.89 wavelengths, working in the protected part of the L-band spectrum (1400 – 1427 MHz). The main subsystems were:

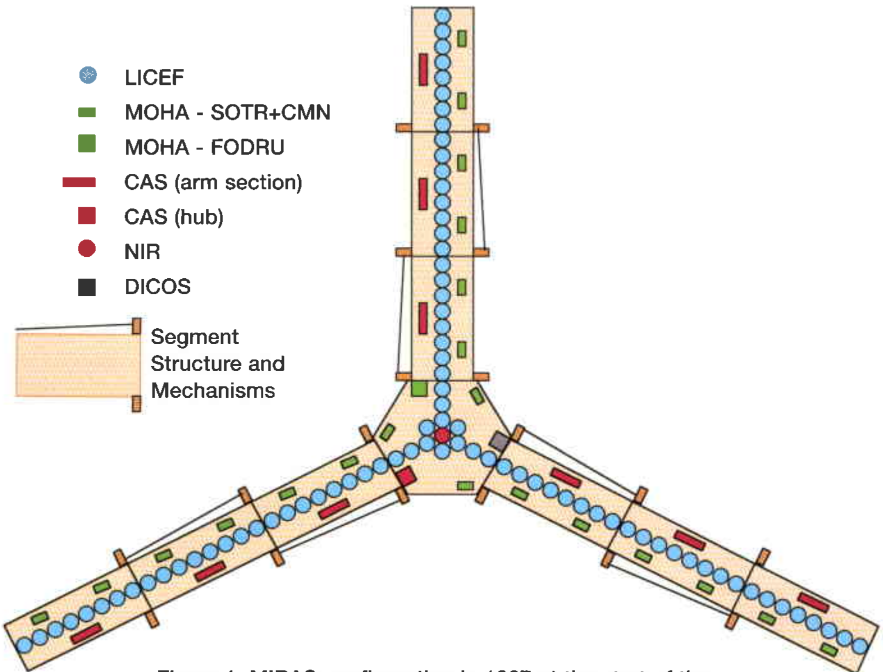


Figure 1. MIRAS configuration in 1997 at the start of the MIRAS Demonstrator Pilot Project

Figure 2. First-generation LICEF-1 antenna-receiver units (courtesy of MIER, Spain)

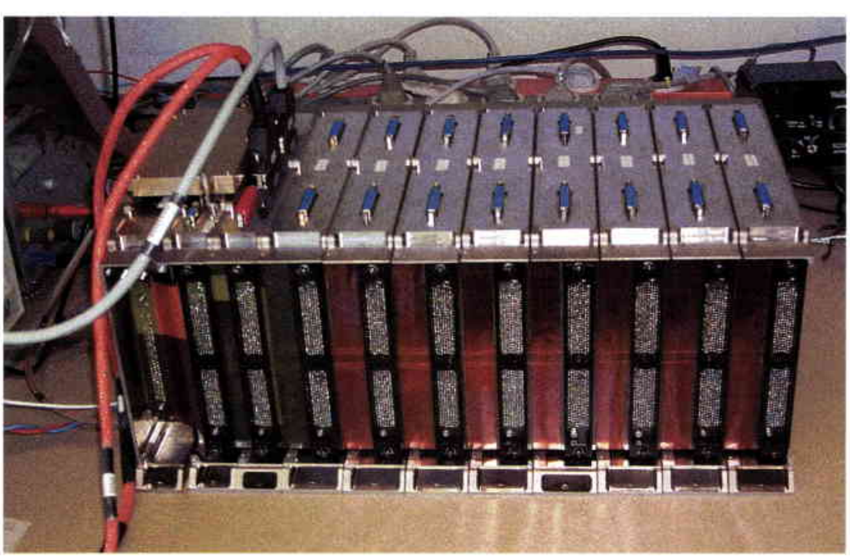


Figure 3. First-generation DICOS-1 digital correlator unit (courtesy of Astrium GmbH, Germany)

- Structure and Mechanisms (STM)
There were three arms segmented into three parts, unfolding in one plane like a solar array, with identical hinges and mechanisms at each of the nine joints. The mechanical design had to be compatible with the electrical harness running along the arm, and would serve the important role of ground plane for the antennas.

- Lightweight Cost-Effective Front-end (LICEF)
These were the antenna-receiver integrated units, responsible for receiving the thermal radiation in the two polarizations (horizontal and vertical), low-noise amplification and filtering. These receivers would down-convert the signals to their in-phase and quadrature components, providing their 1-bit digitised versions as outputs. In addition, each LICEF would also have a Power Monitoring Signal (PMS) that would provide an analogue output voltage proportional to the system temperature.

- MIRAS Optical Harness (MOHA)
The eight digital outputs from each group of four LICEF receivers plus two additional bits for alignment and error detection, would be multiplexed together and converted into an optical signal in a Serial Optical Transmitter Receiver (SOTR) unit. Every segment of the arm would have two such SOTR units, with another three units in the hub (central part of the array). The signals would be transmitted along the arms through an optical fibre to a Fibre Optic Data Receiver Unit (FODRU), which would de-multiplex them.

- Advanced Digital Correlator System (DICOS)
The digital outputs of FODRU would be routed to this central correlator, where all possible pairs of correlations between the signals from all receivers would be performed. The output correlations would then constitute the raw instrument data.

- On-board Calibration System (CAS)
The instrument would be equipped with an on-board calibration system, relying on the injection of uncorrelated and correlated noise immediately after the antenna. The correlated noise injection would be 'centralised' for the hub and 'distributed' for the arms.

Manufacture of the first-generation prototypes of the most critical subsystems, namely LICEF-1 (Fig. 2) and DICOS-1 (Fig. 3), had already begun a year earlier in 1996 and was well under way, with the correlator unit the one nearest to completion.

MIRAS Demonstrator Pilot Project - 1
During 1997, it was realised within the Payload

Systems Division that, to demonstrate the technology of a distributed system like MIRAS, a representative part of the whole instrument had to be breadboarded and tested end-to-end. That is, we had to go beyond subsystem manufacturing and move to the system level to really consolidate the technology of aperture-synthesis radiometers, including calibration. This was necessary to prove not only the electrical performances, but also the mechanical design and signal harness. It was therefore proposed to set up the MIRAS Demonstrator Pilot Project (MDPP-1) activity to manufacture one entire segment of the arm, together with some other units located in the hub of the platform needed to complete the system. MDPP-1 therefore includes:

- the SMOS parametric mission design
- the STM for a complete segment, including the deployment mechanism
- four LICEF antenna-receivers
- the CAS system to service one entire segment and the complete hub
- the MOHA to service one entire segment or the complete hub.

MDPP-1 is funded from the ESA Technology Research Programme (TRP), with the various subsystems being financed through the General Support Technology Programme (GSTP). EADS-CASA (Spain) was selected as the main contractor as Spain is providing the highest GSTP contribution for this activity. EADS-CASA has been entrusted with the technical and management co-ordination for all subsystems and is also responsible for the delivery of the fully tested MIRAS demonstrator to ESA. The activity was kicked-off in September 1998 and the contract is due to end in October 2002.

- SMOS parametric mission design

GMV and EADS-CASA (Spain) were responsible for performing a mission analysis, supported by Spain's Polytechnic University of Catalunya (UPC). This task, carried out during 1998, had the objective of sizing the main parameters of a dual-frequency MIRAS to meet a reasonable set of scientific requirements. This ensured the breadboarding of a representative part of a sound instrument, based on scientific requirements derived from previous studies, both European and American. Once SMOS had been approved as an ESA Earth Explorer Opportunity Mission, the mission analysis was repeated during the Phase-A with the full involvement of the SMOS Science Advisory Group.

An artist's impression of the results of the SMOS parametric mission design effort within MDPP-1 is shown in Figure 4.

The SMOS Mission

The SMOS mission is designed to observe two environmentally very important variables - soil moisture (SM) over land, and ocean-surface salinity (OS) - by L-band microwave imaging radiometry. SMOS will also provide information on root-zone soil moisture, vegetation and biomass and contribute to research on the cryosphere. Knowledge of the global distribution of soil moisture and ocean salinity with adequate spatial and temporal sampling is expected to significantly improve weather, climate and extreme-event forecasting.

Soil moisture and ocean salinity need to be mapped on a global scale and with adequate spatial and temporal sampling, which the SMOS mission will do for the first time. The main requirement for mapping soil moisture from space is suitable accuracy for hydrological and meteorological models, coupled with adequate temporal sampling. Recent studies show that determining soil moisture to 4% accuracy (volumetric) every 3 days is sufficient for most purposes. The spatial-resolution requirements are linked to the specific applications, ranging from 50 - 100 km for global-circulation models, to 20 km or even less for hydrology and agronomy.

The sensitivity of L-band radiometer measurements of ocean brightness temperature to surface salinity is well-established, and it is possible to obtain ocean-salinity estimates if the other perturbing factors (roughness, wind, spume, sun glint, rain, etc.) can be accounted for. The sensitivity of the brightness temperature to salinity is about 0.5 K/psu (psu = practical salinity unit) at a water temperature of 20°C, decreasing to about 0.25 K/psu at 0°C. Given that the sensitivity of state-of-the-art radiometers is ~1K, individual observations cannot meet the requirements of the Global Ocean Data Assimilation Experiment (GODAE), which are 0.1 psu accuracy, a spatial resolution of 2 deg x 2 deg, and a 10-day revisit frequency. They can, however, be met by averaging SMOS measurements spatially and temporally, provided any systematic errors are kept very low by, for example, frequent calibration.

The SMOS satellite re-uses the generic Proteus platform developed by CNES for a variety of missions, the first of which, Jason-1, was launched earlier this year. The platform's main body is a cubic structure (sides of ~1 m) containing all of the equipment needed to store and process the on-board data, power, monitor and control the radiometer; and stabilise its operating temperature. Proteus also provides the orbit acquisition and maintenance capabilities for the planned three-year mission lifetime (extendable to five years) and for precise attitude control and determination. The platform and the radiometer each weigh approximately 300 kg.

The SMOS operational orbit is Sun-synchronous, with local solar times equivalent to 6:00h and 18:00h at the equator crossing. Such a 'dawn-dusk orbit' improves mission performance, due mainly to the more stable thermal observing conditions. The orbital altitude will be 755 km. The satellite design is compatible with several launch vehicles (Rokot, PSLV, Dnepr) and launch is planned for early 2007.

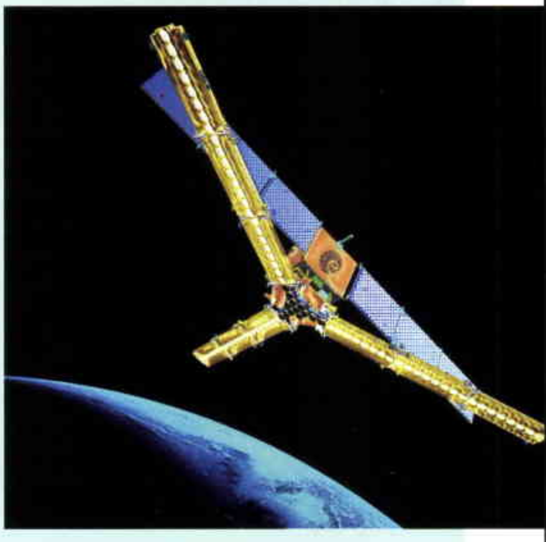


Figure 4. Artist's impression of MIRAS on Minisat following the mission-analysis performed within MDPP-1, at the end of 1998 (courtesy of EADS-CASA, Spain)

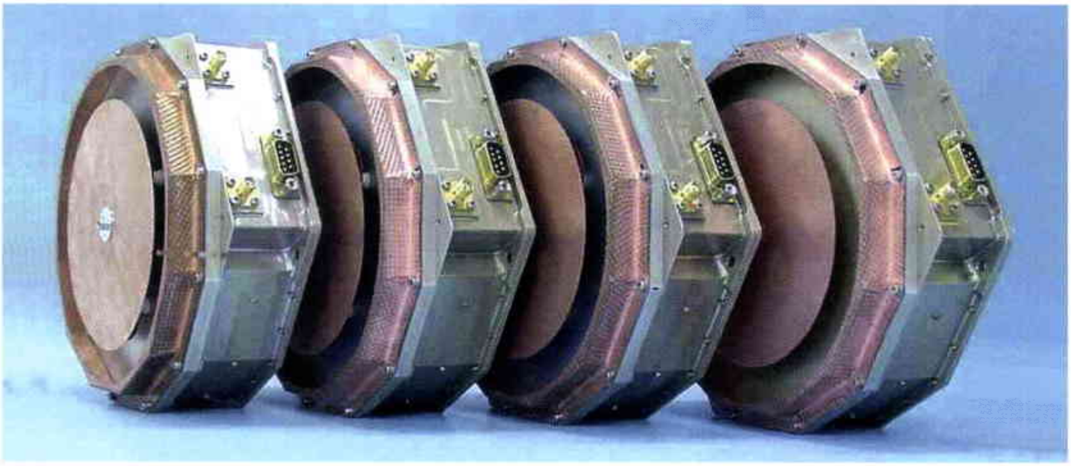


Figure 5. Four second-generation LICEF-2 antenna-receiver units produced within MDPP-1 (courtesy of MIER, Spain)

- STM-1

The structure and mechanisms developed within MDPP-1, designated STM-1 for short, have been developed by EADS-CASA. All segments of MIRAS are identical, there being only one type of mechanism. Deployment demonstrations for one segment (the first one), simulating the mechanical loading of the other two in ambient conditions, together with thermal-vacuum tests on the mechanism, have confirmed the feasibility of the proposed mechanical design and its hardware implementation.

- LICEF-2

The second-generation Lightweight Cost-Effective Front-ends (LICEF-2) have been developed based on the LICEF-1 experience (Fig. 5). MIER (Spain) has overall responsibility for this integrated antenna-receiver unit, and has manufactured its electronics. EADS-CASA has designed and manufactured the antenna and the receiver band-shaping RF filter, while UPC has provided key support in elaborating the technical specifications. MIER has delivered four end-to-end tested LICEF-2 units within MDPP-1.

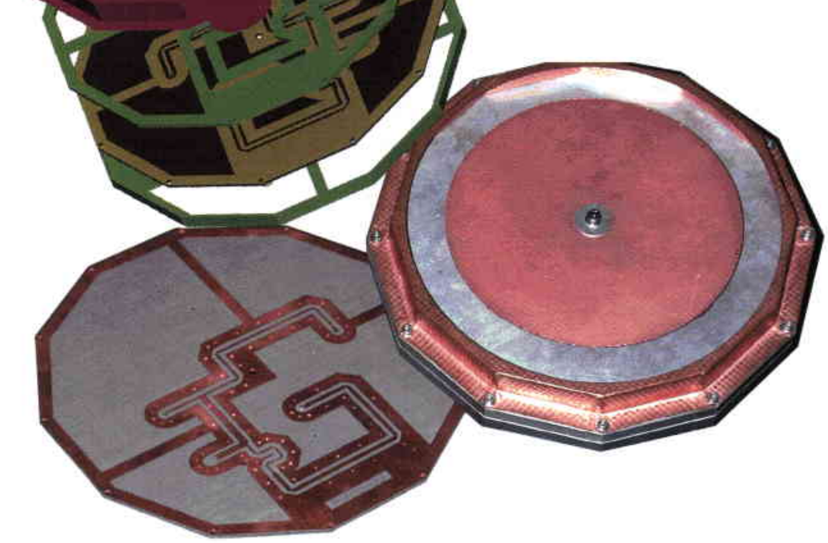


Figure 6. LICEF-2 antenna with its intermediate-layer circuit (courtesy of EADS-CASA, Spain)

(a) Antenna

The electrical design requirements for the basic MIRAS antenna element were derived from the interferometric performance expected from the instrument. The antenna was therefore designed to achieve best performance in terms of gain, bandwidth, co-polar to cross-polar ratio over the field of view, coupling between polarisation ports, and phase-centre localisation.

The requirements for phase-centre localisation and cross-polarisation performance over the field of view (33 deg around boresight) have driven the design in terms of the number of probes and their locations. The solution adopted consists of four probes balanced in pairs, located 180 deg apart and rotated 90 deg for each polarisation. This approach achieves the required 25 dB co-polar to cross-polar ratio, and confines the phase centre for both polarisations to within less than 0.5 mm around the patch's geometrical centre. The effect on the antenna pattern of using a germanised kapton foil for thermal protection has been shown to be negligible.

An intermediate layer has been included between the antenna and the RF circuitry (Fig. 6) for two reasons. Firstly, it is used to combine the received signals at the two probes with the same polarisation and to provide a single connection to the circuitry beneath. Secondly, with the three-layer design, the antenna can be rotated with respect to the receiving circuit, so that the box, the electronics and connectors remain in the same position with respect to the mounting arm, but all antennas on the three arms are aligned.

(b) Receiver electronics

The main elements of LICEF are the dual-polarisation patch antenna and the down-converter. They are integrated to form a mechanically compact sub-unit, which can be easily and separately tested before integration into MIRAS.

The receiver converts the 1.4 GHz signal from the target into two intermediate-frequency (IF) signals, I and Q, at 8–27 MHz. The IF signals are analogue-to-digital converted by 1-bit samplers at a rate of 56 Mbit/s and finally output optically for cross-correlation. These signals contain the phase information about the received signal. The local oscillator (LO) signal is fed to all LICEFs through equal-length paths to maintain phase coherency between them. In addition to the digital outputs, the total power is measured at the IF part by a Power Measurement System (PMS) for source temperature definition. To meet the radiometric-accuracy requirement, a highly linear and stable PMS is needed.

The RF and IF amplifiers, filters and mixers of an interferometric receiver are the critical parts with respect to the performance requirements. In LICEFs, custom-designed MMICs are used where applicable, as monolithic circuits diced from a single wafer are known to provide excellent uniformity. With such a customized approach, it is also possible to address low power consumption by appropriate circuit design, which is also an important issue for this system. A European foundry (Ohmic, France) has been selected to supply the GaAs MMIC chips.

The low-noise pre-amplifier (LNA) module is a conventional hybrid design to minimise losses and noise figure. Its active elements are European HEMT chips, which have a minimum noise figure of less than 0.24 dB at 1.4 GHz. The overall receiver noise figure is increased to 2 dB, however, due to several components that are necessary ahead of the LNA, such as the calibration RF switch, isolator, and antenna.

Although MIRAS operates in the protected 1.4 GHz frequency band, there are strong interfering sources such as radars operating just outside it that could be harmful for radiometry. To reduce the level of the expected in-orbit interference, therefore, very sharp filtering is required using a Chebyshev comb-line design with eight tunable resonators. The RF filter's other important role is to make the frequency response of all receivers as identical as possible, which translates into a good fringe-washing function.

The PMS in the LICEF performs the power-to-voltage conversion of the received signal. Although the PMS could, at its simplest, be a single diode, considerable effort has been invested in designing a PMS that is highly stable over a wide temperature and dynamic range, in striving for the optimum solution.

- CAS-1

The MIRAS onboard Calibration System in MDPP-1 (CAS-1) is the responsibility of the Helsinki University of Technology and of Ylinen (Finland). This system is based on the injection of correlated and uncorrelated noise into all the receivers of the MIRAS array. Matched loads inside the LICEF receivers provide the uncorrelated noise, while the injection of correlated noise is centralised within the hub and distributed along the arm arrays, as proposed by UPC in earlier studies.

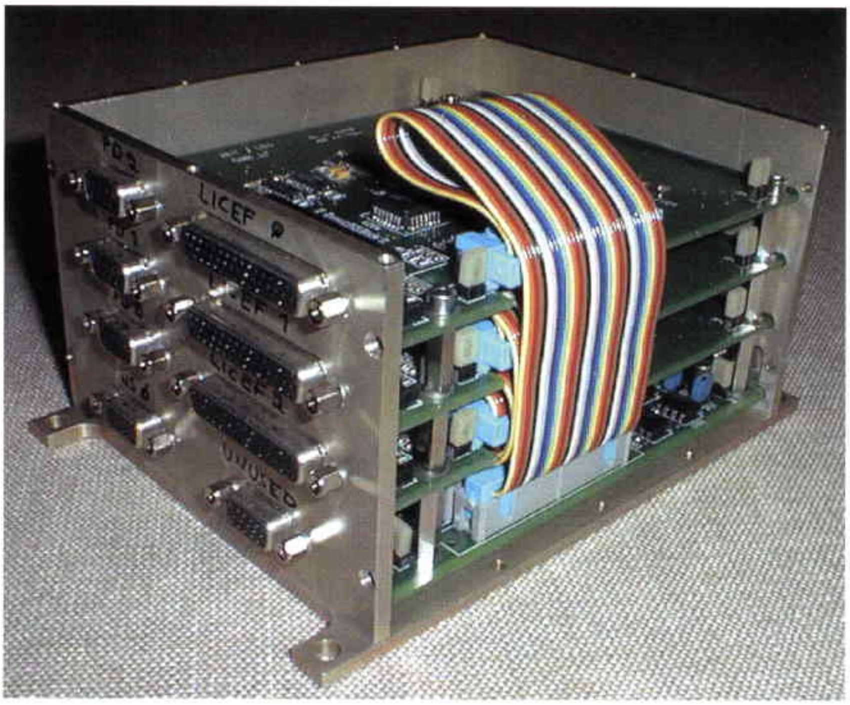
CAS-1 is made up of noise-source and power-divider housings, control and monitoring nodes and phase-matched cabling to service the LICEF receivers. The hardware has been built and completely characterised at subsystem level. Figures 7 and 8 show the control and monitoring node, as well as the hub noise source and power-divider housings.

- MOHA-1

Verhaert, Siemens Atea and Nexans (Belgium) are responsible for the MIRAS Optical Harness in MDPP-1 (MOHA-1). Verhaert is the subsystem prime contractor, responsible for space issues and mechanical design, Siemens designed and manufactured the hardware, and Nexans provided the optical fibres.

MOHA-1 is an optical connection that brings the digital I and Q samples from all LICEF receivers down to the central correlator unit (DICOS). The optical harness consists of multiplexer boxes along the arm and a demultiplexer close to the central correlator. This multiplexing into groups of four receivers, together with the use of optical fibre, reduces

Figure 7. Control and Monitoring Node (CMN) of the CAS on-board calibration system (courtesy of HUT, Finland)



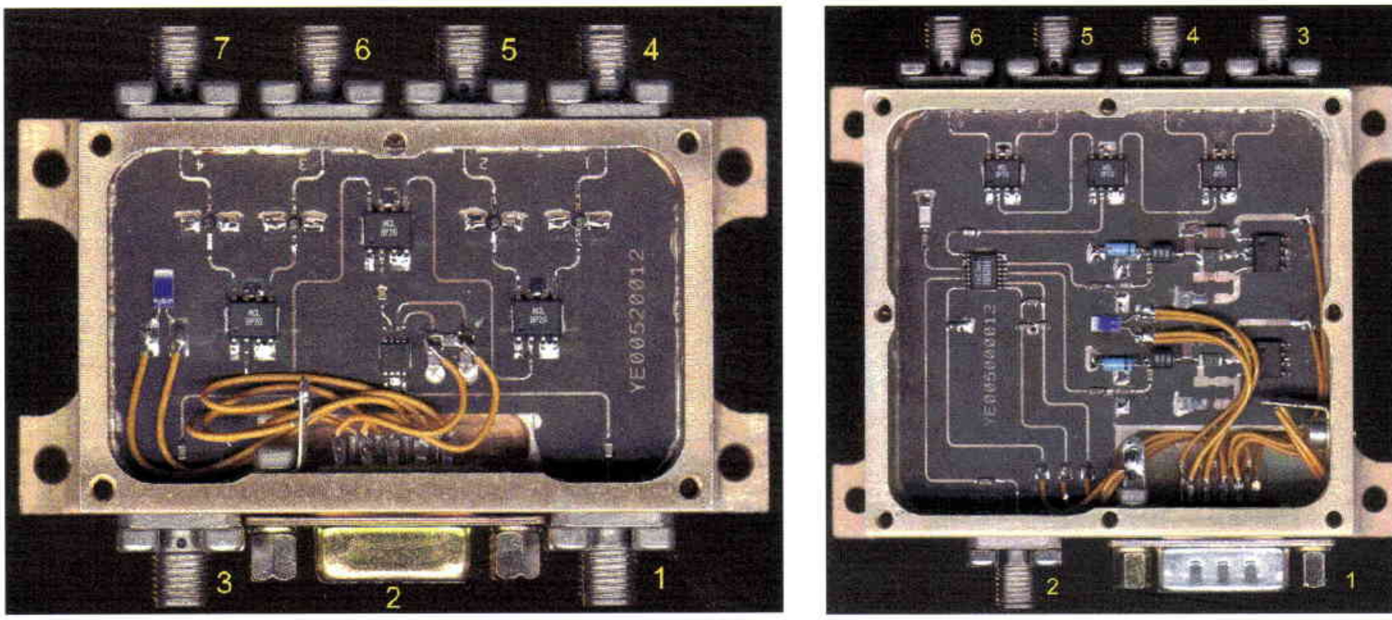


Figure 8. On-board calibration system (CAS) hardware, with the Power-divider (left) and Noise-diode (right) housings (courtesy of Ylinen, Finland)

the number of lines needed and the mass of the harness, which is very important for its routing and its impact on the deployment mechanisms. The data rate is 10 times the sampling clock (about 560 Mbit/s). Two very similar ASIC circuits, one for the multiplexer and the other for the demultiplexer, have been developed in MOHA-1. The optical harness also serves to generate and distribute the reference clock signal, the heart of the instrument, as its operation must be fully coherent. This uplink goes through one optical fibre per multiplexer. Each multiplexer then distributes it to four LICEF receivers. LICEF uses a Phase Lock Loop circuit to lock its voltage controlled oscillator to this reference, thereby achieving coherent operation throughout the array.

Figure 9 shows the Serial Optical Transmitter Receiver (SOTR) unit.

- DICOS-1

The advanced MIRAS Digital Correlator System (DICOS-1) was developed under a contract with Astrium GmbH (Ottobrun, Germany) prior to MDPP-1. This unit, which has 18 000 correlators working at 1-bit and 56 MHz, performs onboard cross-correlation of the signals between any pair of antenna elements in the array. These correlations are samples of the so-called 'visibility function', which is essentially the Fourier transform of the image's brightness distribution. This raw MIRAS data (order 100 kbit/s) is downloaded to Earth for image processing. DICOS has been built around a 17x17 (289) correlator ASIC circuit, with each ASIC having about 100 kgates in 1.0 micron-gate-length 3.3 V CMOS technology.

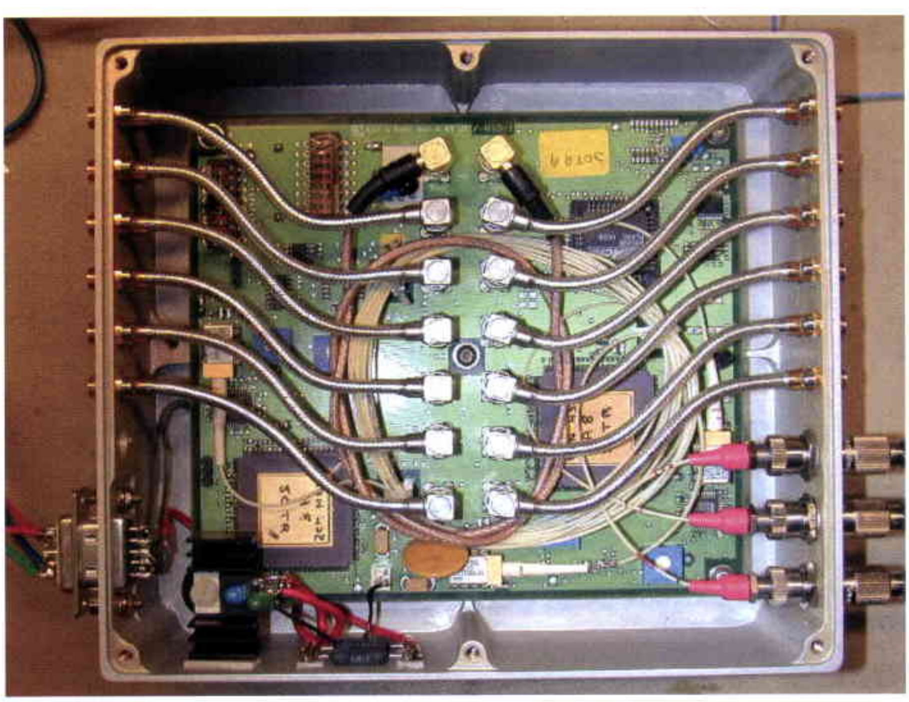
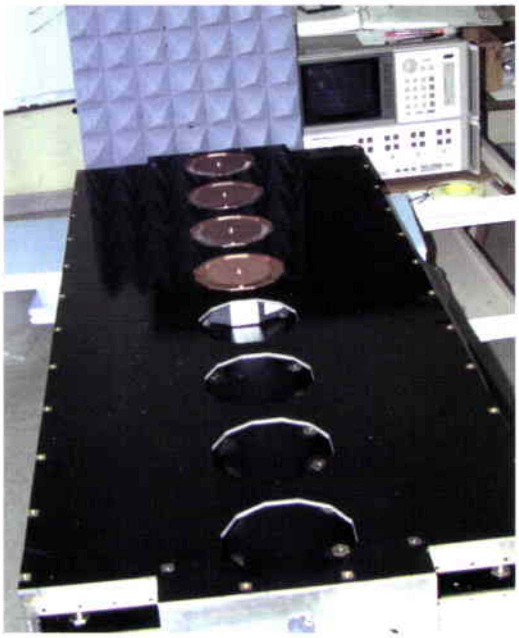


Figure 9. Serial Optical Transmitter Receiver (SOTR) unit of the MOHA optical harness (courtesy of Verhaert and Siemens, Belgium)

MIRAS Demonstrator Integration and Test

All LICEF subsystems, MOHA, CAS and DICOS have been delivered to EADS-CASA and the MDPP-1 activity has now entered its final phase, namely assembly, integration (Fig. 10) and testing of the complete MIRAS demonstrator. The companies responsible for the different subsystems developed their own particular Electrical and Mechanical Ground-Support Equipment (EGSE and MGSE) to perform the subsystem-level testing. The division of responsibilities at system level is as follows: EADS-CASA for MGSE and HUT for EGSE and the execution of full system end-to-end electrical tests, already performed in an anechoic chamber at the Technical University of Denmark (DK).



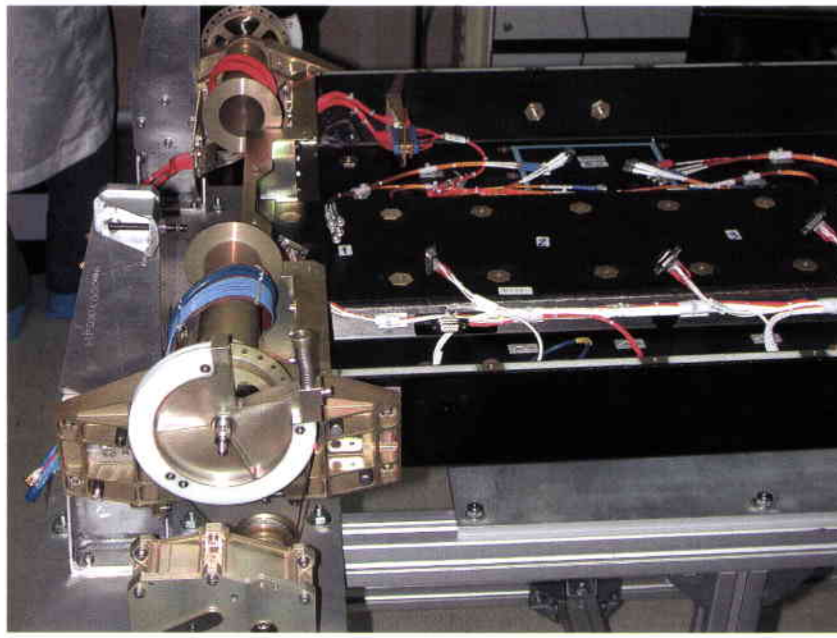


Figure 10. First steps in the integration of the MIRAS demonstrator in MDPP-1. Left: integrating the LICEF-2 receivers. Right: wiring the harness. (courtesy of EADS-CASA, Spain)

MIRAS Demonstrator Pilot Project - 2

Early in 2000, an MDPP-1 follow-on activity was prepared under the title 'Validation of L-band Image Radiometry', known as MDPP-2 for short, the objectives of which are to advance the demonstration of the technology feasibility of MIRAS through:

- a Deployment Demonstration Test for one complete arm (three segments)
- an Image Validation Test using a 12-LICEF MIRAS array
- three proof-of-concept activities involving: a Noise-Injection Radiometer (NIR), an advanced correlator unit (DICOS-2), and an advanced band-pass filter (BFP-2), and
- the breadboarding of the optical harness from SMOS-Phase-A (MOHA-3).

Unlike MDPP-1, the core funding for MDPP-2 comes from the GSTP budget, which covers the deployment demonstration, the image validation and NIR. DICOS-2 and BPF-2 are TRP-funded subsystems. The industrial companies involved in the GSTP share are the same as in MDPP-1, except for the addition of Toikka (Finland) and Contraves (Switzerland). The subcontractor selected for DICOS-2 is Astrium GmbH (Germany), with EADS-CASA responsible for BPF-2. The MDPP-2 contract was kicked-off April 2001, with a planned end-date of June 2003.

- Deployment Demonstration Test

This test implemented by EADS-CASA involves, in addition to the available first segment from MDPP-1, the manufacture of:

- the structures of the second- and third-arm segments
- the mechanisms (except for the hold-down and release mechanisms)
- the synchronisation hardware, and
- the mechanical dummies of the electronic units.

- Image Validation Test

This test is the responsibility of EADS-CASA, strongly supported by UPC and with the participation of the subsystems companies as indicated below. Its objective is the recovery of a known brightness-temperature scene within the specified spatial resolution, radiometric resolution and accuracy. The reference scene will be taken inside an anechoic chamber at INTA's facilities in Spain, in two different situations: when there is a constant brightness distribution provided by the chamber absorbers at ambient temperature, and when there are two point sources simulated by two probe antennas placed within the useful instrument field of view.

- NIR

The Noise-Injection Radiometer (NIR), which is being developed by HUT, Ylinen and Toikka, performs the following functions:

- measurement of the antenna temperature with fully polarimetric capability, needed for the retrieval of the polarimetric brightness temperature maps
- measurement of the output power of the hub centralised noise source of CAS, required to perform amplitude calibration.

The NIR is a pulse-injection radiometer operating with a Dicke reference load. Its core electronics and antenna are identical to those of LICEF, as both units must be as similar as possible to achieve the best performance. The NIR successfully completed its Critical Design Review in June 2002. For redundancy reasons, the MIRAS Phase-A configuration includes two such NIR units.

- DICOS-2

Astrium GmbH is responsible for the manufacture of MDPP-2's advanced second-generation Digital Correlator System, DICOS-2, which also passed its Critical Design Review in June 2002. Its new features compared to DICOS-1 are:

- new DICOS ASIC development, in a technology suitable for space application
- fringe-washing capability
- dual-polarisation and full-polarisation operation, and
- enhanced redundancy.

- BPF-2

The development of an advanced RF Band-Pass Filter in MDPP-2 (BPF-2) is being carried out by CASA-EADS. BPF-2 is an optimised design based on the one already produced for the LICEF-2 receivers. A slightly lower mass, a more robust connector fixing, and venting holes are some of the improved features. The Test Readiness Review is planned for July 2002.

Image validation using the HUT-2D radiometer

HUT, together with Ylinen, started the development of an airborne 36-element U-shaped two-dimensional interferometric radiometer back in 1996, financed by the Finnish National Research Technology Programme. Within the MDPP-1 calibration activities described above, the Finnish team became involved in the implementation of the MIRAS onboard calibration system in their airborne instrument. By 2000, the development of the HUT-2D instrument had slowly progressed and a new contract was placed by ESA's Earth Observation Directorate to finally push the instrument towards completion. A two-step strategy is currently being followed, first performing tower-based tests with only eight receivers, before the final production of the 36 receivers for the aircraft flights.

Image validation using the LICEF-1 receivers

Several image-validation test campaigns were carried out using the LICEF-1 receivers (cf. Fig. 2) within the Payload Systems Division at ESTEC and by the University of Valencia, the objective being to obtain absolutely calibrated images of the Sun, Moon and cold sky. A small version of MIRAS was built with eight-element-long arms and a Y-shaped structure. A simple 12-correlator unit (DICOS-3) developed specially by Astrium GmbH was used for this particular experiment, which was performed in the Dwingeloo (NL) radio observatory's premises to avoid interference.

Figure 11 shows the image of the Sun. Absolute accuracies in the 4% range were achieved, which was well within the error bars of the relatively simple setup and signal processing applied.

From technology research to Phase-A: instrument evolution

As explained above, the instrument configuration for the MIRAS Demonstrator

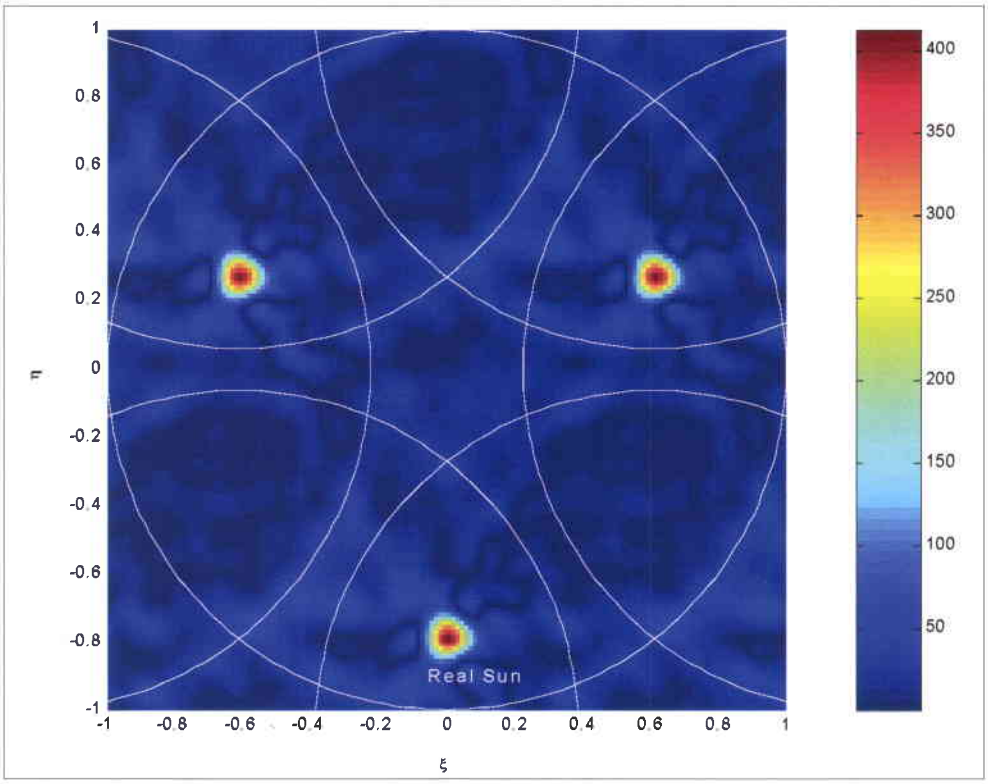


Figure 11. Solar image acquired using the LICEF-1 receivers and the DICOS-3 correlator unit. The real Sun is at 6:00; those at 10:00 and 2:00 are aliases, as expected

Pilot Project responded to the objective of technology-feasibility demonstration, rather than to meeting specific scientific requirements. Late in 1998, however, a proposal led by Y. Kerr (CESBIO, France) and J. Font (ICM, Spain) for the SMOS mission was submitted to ESA, and approved as the second Earth Explorer Opportunity Mission one year later. The SMOS Phase-A was started in September 2000 and, within this framework, a proper sizing of the MIRAS instrument was then performed by industry with a thorough mission analysis. The industrial study was guided by the SMOS Science Advisory Group, established specially for the purpose.

The resulting refined scientific requirements, together with the technical constraints on the mission, led to a somewhat smaller MIRAS instrument than that of MDPP. There were also some changes to the detailed architectures of the various subsystems, the optical harness being the most modified because the signals were no longer to be multiplexed. The MOHA-3 activity at Contraves (CH), mentioned earlier, is aimed at breadboarding the new optical harness within MDPP-2. The MIRAS configuration at the end of the SMOS Phase-A is shown in Figure 12.

The MIRAS Demonstrator Pilot Project provided invaluable experimental data during the SMOS Phase-A, continues to do so during the present Pre-Phase-B, and will do the same again during SMOS Phase-B, which has been approved with a planned start around November 2002.

Conclusion

The Demonstrator Pilot Project has brought together the development of the various subsystems to demonstrate MIRAS's feasibility and imaging performance right up to system level. The progress in the development of the HUT-2D airborne radiometer, the results of a Sun image validation test and an overview of the SMOS mission have also been presented here. Based on the results that have been achieved, in summarising the status of technology readiness of MIRAS for the SMOS mission, we can state with confidence that all critical areas have been successfully covered. We look forward to reporting on the first images from SMOS in the ESA Bulletin some five years from now!

Acknowledgements

The MIRAS Demonstrator Pilot Project is the result of excellent team work by three Divisions within the ESA Directorate of Technical and Operational Support, in conducting key instrument pre-development work for the ESA Directorate of Earth Observation. We would like to acknowledge the excellent work carried out by EADS-CASA (E) and the industrial team: Astrium GmbH (D), Contraves (CH), GMV (E), HUT (Fin), MIER (E), Nexans (B), Siemens (B), Toikka (Fin), TUD (DK), UPC (E), Verhaert (B), and Ylinen (Fin).

The contributions to the project from the Spanish Trainees who spent time with the ESTEC Payload Systems Division in the last four years also deserve a special mention.

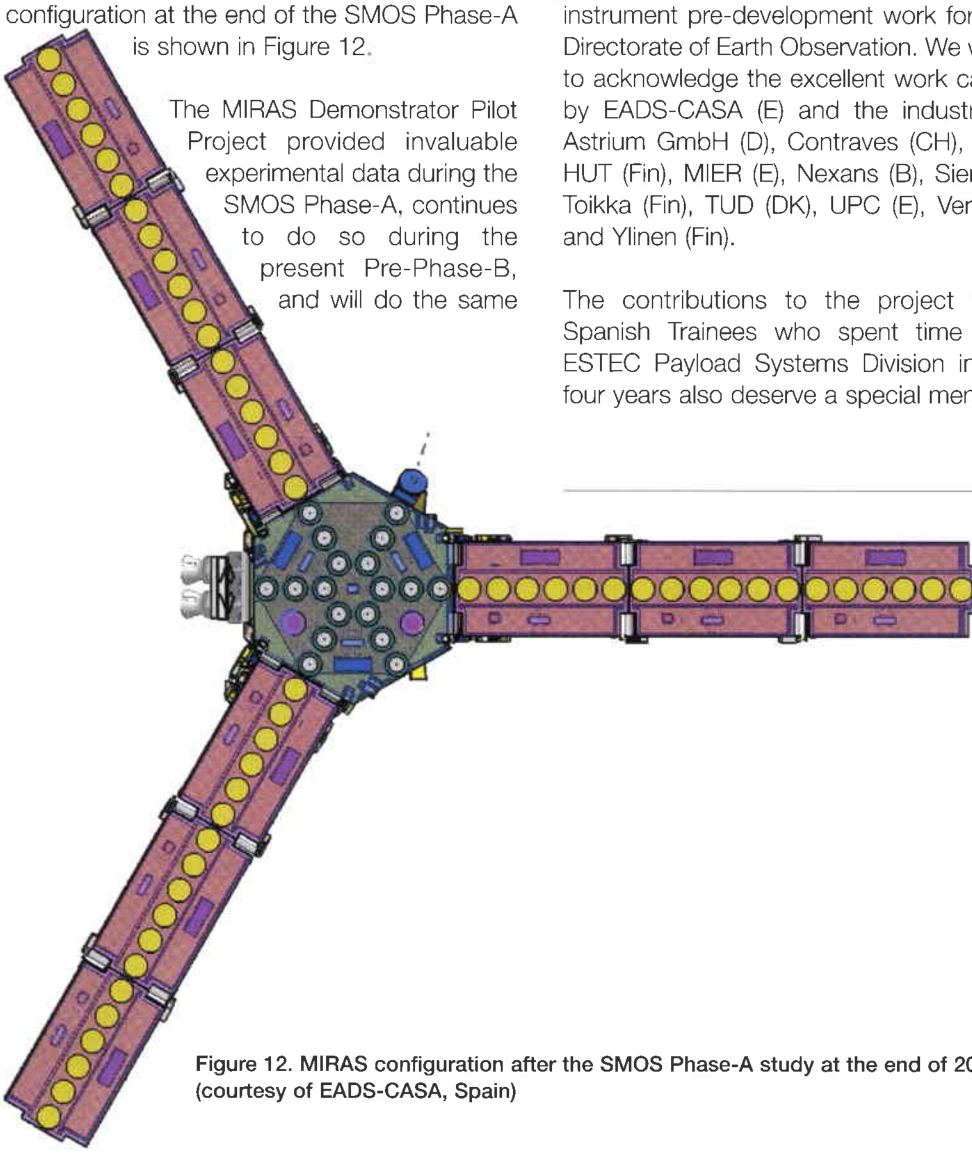


Figure 12. MIRAS configuration after the SMOS Phase-A study at the end of 2001 (courtesy of EADS-CASA, Spain)

Introducing ECSS Software-Engineering Standards within ESA

– Practical approaches for space- and ground-segment software

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In June 1994, the ESA Council adopted a resolution that confirmed the Agency's commitment to transferring the existing system of ESA space standards to a new set of standards that were to be prepared by the European Cooperation for Space Standardization (ECSS). For software engineering, this has meant moving from the ESA PSS-05-0 to new software standards: ECSS-E-40 for software engineering and ECSS-Q-80 for software product assurance, both of which are based on a new international standard, ISO/IEC 12207. In addition, to cover the full scope of the old standard, it is also necessary to use the ECSS management standards (the ECSS-M series). Adoption of a new standard is a major change and one that has to be undertaken with care and so this article describes the measures that were taken to ensure a smooth transition, both at ESTEC for space-segment software and at ESOC for ground-segment software.

Why a new software-engineering standard?
ESA has had a highly successful software-engineering standard, ESA PSS-05, since 1984. PSS-05 was prepared by ESA's Board for Software Standardisation and Control (BSSC), which was established in 1977, when the importance of software standards for the proper conduct of complex or critical space-software projects was realised. PSS-05 appeared in Issue 1 in 1984, followed by Issue 2 in 1991. The BSSC also wrote a set of guides to provide more detailed assistance in using PSS-05. Both the standard and the set of guides were published as books.

However, the Council decision in 1994 meant that no further issues of PSS-05 would be published and the new ECSS software-engineering standard would become the one to be used in ESA software projects. Shortly after this decision, ISO published a new international software-engineering standard, ISO/IEC 12207 (Information Technology, Software Lifecycle Processes, 1995), which is now the leading standard in this field. The ECSS software-engineering standard ECSS-E-40, which first appeared in 1999, is based on ISO 12207. In fact, ECSS-E-40 tailors ISO12207 specifically for space projects.

The introduction of this new standard represented a further step in the 'Europeanisation' of the way of working in the Agency. In fact, an objective was to produce a standard to be used throughout the European space business, i.e. by Industry and across the space agencies within Europe, superseding agency-specific standards such as PSS-05. In this way, the problem of a given company or consortium having to follow different standards depending on which agency it is contracted to for any given development is avoided: the ECSS standards thus provide a common backbone.

This European approach also had consequences for ESA's BSSC: whereas formerly the BSSC established and maintained software-engineering standards, now this responsibility is transferred to the ECSS. Of course, the BSSC has in practice been involved in the relevant ECSS Working Group and subgroups – for example, one of the BSSC Co-Chairmen is also convenor of the ECSS-E-40/ ECSS-Q-80 Working Group. Within ESA, the BSSC still plays an important role, since it has to ensure that the new software-engineering standards are introduced and applied properly and that tailoring methods and ESA implementations of the ECSS standards are available as needed. It also deals with standardisation aspects such as coding standards that will not be covered by ECSS. The rest of the BSSC's responsibilities remain unchanged, ensuring in particular that the standards are applied in ESA contracts, and liasing with the ESA's Legal and Contract Departments on matters affecting software intellectual-property rights.

The structure of the ECSS standards is shown in Figure 1, from which it can be seen that there are three main branches: 'Management', 'Product Assurance' and 'Engineering'. It is a characteristic of software engineering that it involves all three branches of the ECSS standards.

Software in ESA

ESA's core business is the execution of space programmes, including:

- space segments comprised of spacecraft, payloads and launchers
- ground segments comprised of all of the ground facilities needed to operate each mission.

Software is pervasive throughout the whole 'product tree' of any space programme: Figure 2 shows a typical space system schematically, with emphasis on the software elements. The space segment has onboard computers, data-handling systems, attitude and orbit control systems, all of which contain software. The ground segment has mission-control systems, simulators, flight-dynamics systems, mission-analysis tools, communications networks and ground-station data systems such as telemetry and telecommand processors, as well as 'downstream processing' systems for payload data. These all contain software, often of considerable complexity.

Developing and maintaining this software in a disciplined way is a key to the success of any space mission. Failure to do this can result in expensive delays, and in the worst case in catastrophic failure. Following proper software standards is one of the ways of keeping software development under control and ensuring adequate quality.

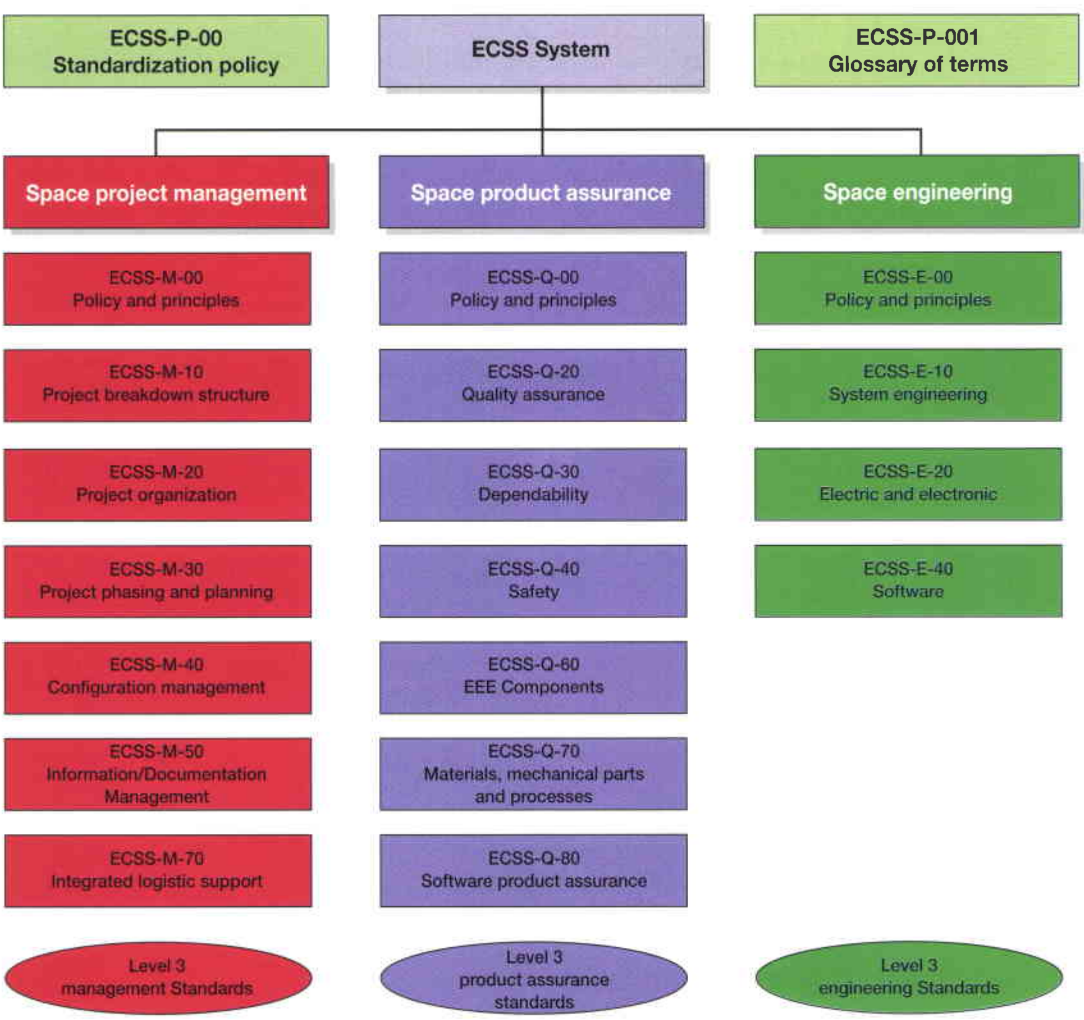


Figure 1. Structure of the ECSS standards

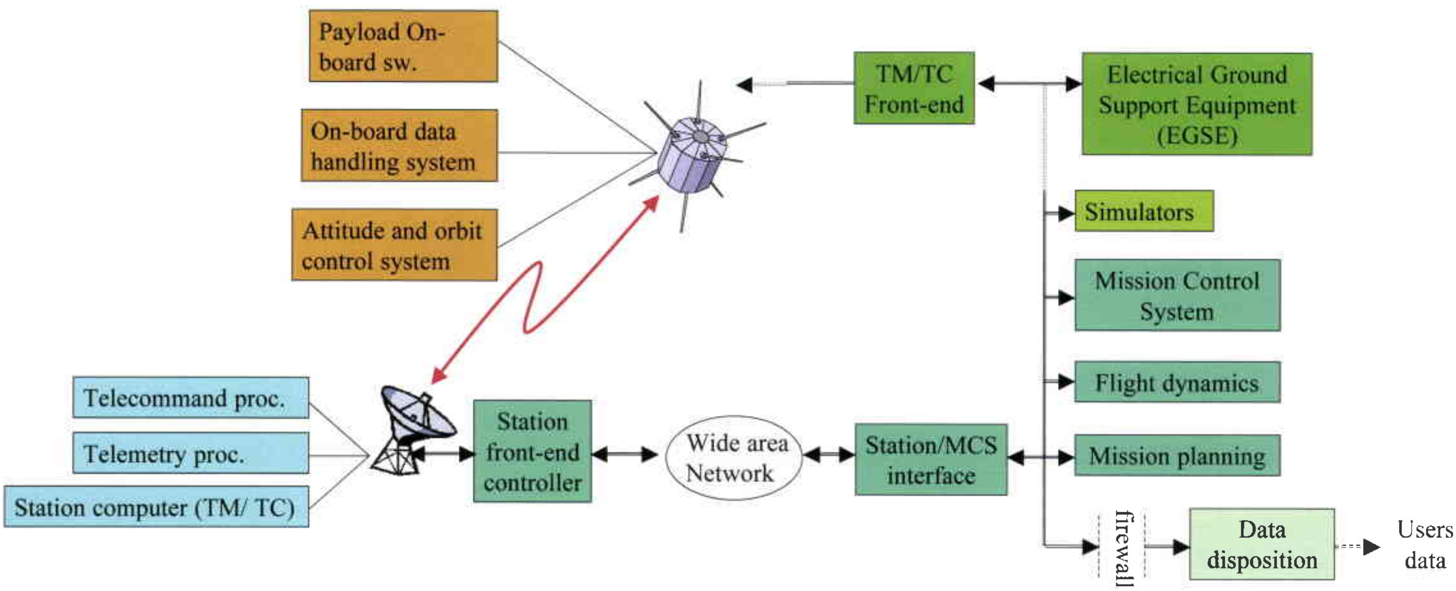


Figure 2. Schematic of a typical space system, with the emphasis on software elements

Overview of ECSS-E-40

ISO 12207 and ECSS-E-40 are based on a defined set of processes. They define:

- requirements on those processes broken down into component activities
- their expected inputs and outputs.

They are in effect 'standards for making standards', the idea being that this permits suppliers to use their own standards, provided that they comply with the requirements of ECSS-E-40 or some tailoring of it defined by the customer. ECSS-E-40 is available at the ECSS Web site: http://www.estec.esa.nl/ecss/, where its partner quality standard ECSS-Q-80 and the ECSS-M standards may also be found.

ECSS-E-40 is based on the customer–supplier concept. As shown in Figure 3, this concept may be applied recursively, as would typically be the case for space projects with ESA as the customer at the top level, and then a chain of customer–supplier relationships extending downwards to the prime contractor and then to the lower levels of subcontractors. Reviews are the main interaction points between the customer and the supplier.

The accompanying coloured panel is a brief review of ECSS-E-40, outlining the required processes, reviews and documentation. It gives the correspondence to PSS-05 where appropriate, for the benefit of readers familiar with that standard. Figure 4 shows the processes of ECSS-E-40 and ECSS-Q-80.

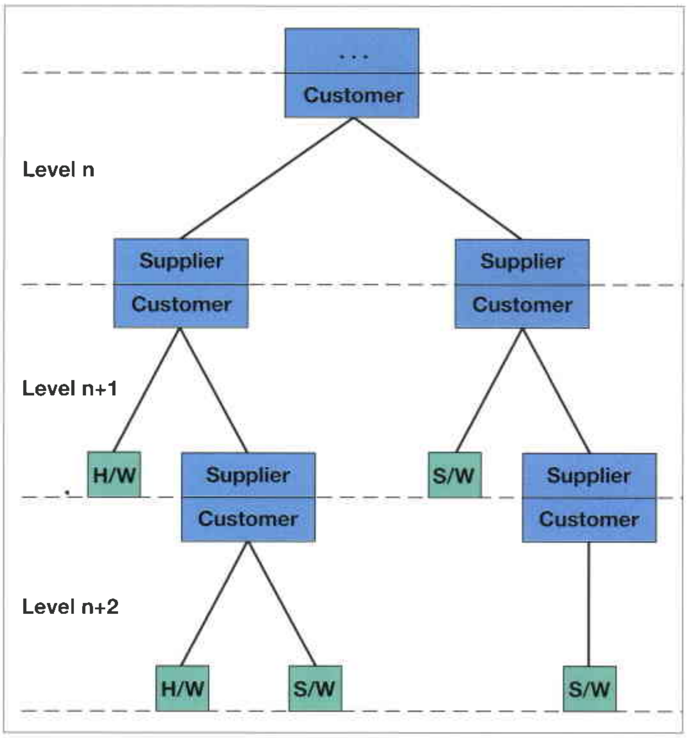


Figure 3. Customer–supplier relationship

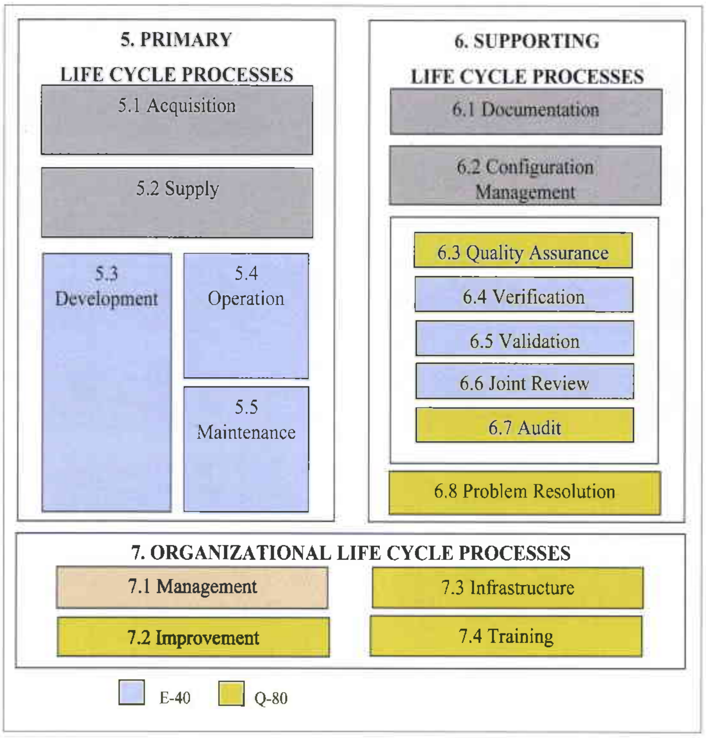


Figure 4. Processes of ECSS E-40 and ECSS Q-80

ECSS-E-40 Processes

System Engineering
This is carried out by the customer and involves such activities as:
- system requirements engineering
- system integration
- system validation.

This is somewhat analogous to the PSS-05 User Requirements (UR) phase, but is more general in that it sees the software as part of a system that put requirements on it – the surrounding system could be onboard hardware and other software systems, and need not necessarily include a human user. In PSS-05, the UR phase was generally understood as a specific activity occurring after the system definition, preparing the software development, but separated from the system activities. In ECSS, this process is the same as the ECSS-E-10 Space System Engineering process, ensuring a better transition of the requirements from system to software.

Software Requirements Engineering
This is carried out by the supplier and in essence involves:
- software-requirements analysis (roughly equivalent to PSS-05 SR phase)
- software top-level architectural design (roughly equivalent to PSS-05 AD phase).

The related review is the Preliminary Design Review (PDR).

Software Design Engineering
This is also carried out by the supplier and involves:
- designing of software items
- coding and unit testing
- integration
- validation with respect to the technical specification (equivalent of PSS-05 System Testing).

The related review is the Critical Design Review (CDR).

Software Validation and Acceptance
This comprises:
(i) Validation with respect to the requirements baseline: the milestone is the Qualification Review (QR), which is carried out in the supplier's environment and is often referred to as the 'Factory Acceptance Test'
(ii) Software delivery and installation
(iii)Software acceptance: the milestone is the Acceptance Review (AR) and is carried out in the operational environment (like PSS-05 Acceptance Test, AT). This is also referred to as the Site Acceptance Test (SAT), and may be preceded by a Preliminary SAT (PSAT). Acceptance is carried out by the customer.

Activities (ii) and (iii) are analogous to the PSS-05 Transfer Phase.

Software Operations Engineering
This comprises:
- preparation of software operations procedures
- preparation of plans for operational testing (i.e. of new releases coming from the maintenance process)
- software operations proper
- user support, including what is usually called 'first-line support', e.g. help desk.

Software Maintenance
This comprises:
- software problem analysis
- software problem correction (software modification)
- re-acceptance (i.e. validation of corrections)
- software migration (cf. PSS-05 'adaptive' maintenance)
- software retirement.

ECSS software maintenance is similar to PSS-05 Operations and Maintenance (OM Phase), but ECSS-E-40 places more emphasis on migration and retirement, and separates first-line maintenance from software operations.

Reviews
The following table summarises the reviews required by ECSS-E-40:

Name	Acronym	Associated process
System Requirements Review	SRR	System engineering
Preliminary Design Review	PDR	Requirements engineering
Critical Design Review	CDR	Design engineering
Qualification Review	QR	Validation and acceptance
Acceptance Review	AR	Validation and acceptance
Operational Readiness Review	ORR	Software operations engineering

Software documentation
Figure 5 shows the main categories of ECSS-E-40 documentation. It is arranged in 'folders', into which the various output documents are aggregated. The main folders are:
– Requirements Baseline (RB)
– Technical Specification (TS)
– Design Definition File (DDF)
– Design Justification File (DJF).

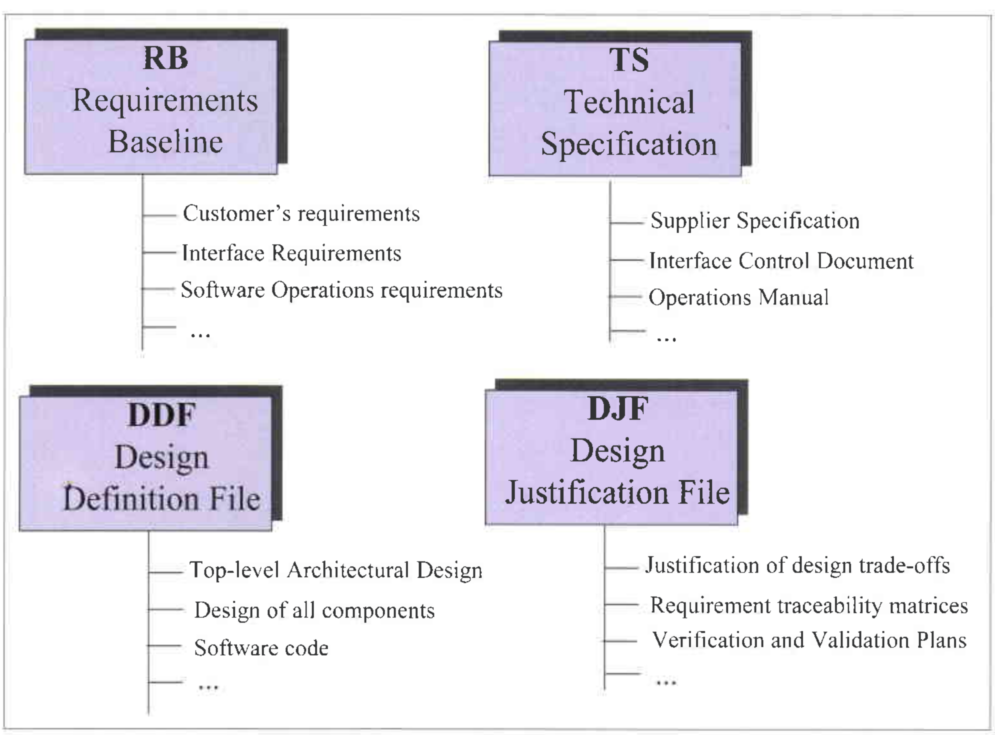
The contents of these folders are built up in the course of the project, as shown in Figure 5. The folders may, of course, be logical, i.e. they may in effect be directories pointing to the documents they 'contain' rather than being physical folders.

Software life cycles
The software life cycle defines the sequencing and dependencies of the processes. As with PSS-05, no particular life-cycle model is imposed, but its selection is an essential management activity. The supplier must document this choice in the Software Development Management Plan.

Comparison of ECSS-E-40 and PSS-05
The BSSC carried out a detailed analysis of ECSS-E-40 and PSS-05, comparing in particular the ECSS-E-40 processes with the PSS-05 phases, including process/phase inputs and outputs, and reviews. The main conclusions were that PSS-05 mandatory practices cover about 70% of the ECSS-E-40 requirements. The analysis also identified ECSS-E-40 requirements not covered by PSS-05-0 practices.

Figure 6 shows a mapping of PSS-05-0 phases to the ECSS-E-40 processes, including related reviews, reflecting the fact that a process model can always be projected into a set of phased activities. Figure 7 illustrates the contrasting features of the two standards, the main ones being:
- process-based (ECSS-E-40) versus practice-based (PSS-05)
- ECSS-E-40 is based on the notion of customer and supplier, while PSS-05 has no such concept
- ECSS-E-40 and ECSS-Q-80 apply to 'product software', i.e. software that is part of a space-system product tree and developed as part of a space project. They are applicable to all the elements of a space system: the space segment, the launch-service segment and the ground segment. By contrast, PSS-05 is general (it could apply to any software) and applies to a software project
- ECSS-E-40 allows the customer to 'tailor' the standard, i.e. the deletion of non-applicable processes, activities or tasks. Tailoring is specified in the customer's request for proposal, and may involve additional unique or special processes, activities or tasks.

Figure 5. Main categories of ECSS E-40 documentation



Transition from PSS-05 to the ECSS set of software standards
In 1996, the BSSC issued an information note to all ESA staff providing information about the planned transition. It also laid down one general principle: it was not required to apply ECSS-E-40 retroactively to projects already using ESA PSS-05, and this still holds true.

Applying ECSS software standards to space-segment projects
Spacecraft onboard software has several features unique for the

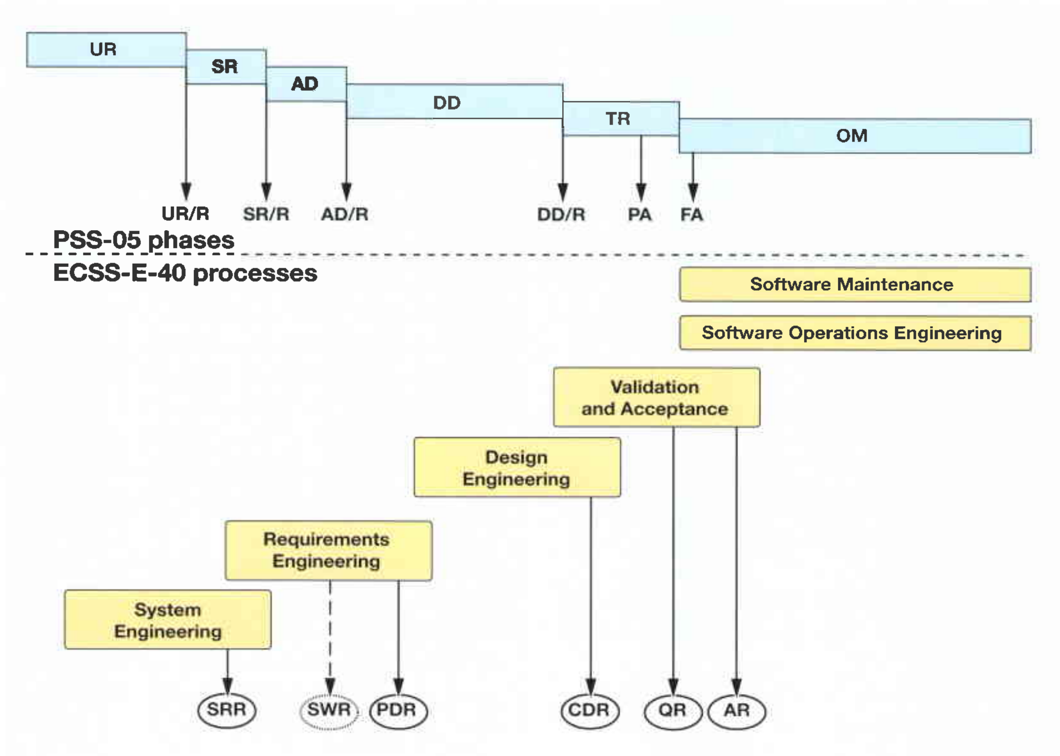


Figure 6. Mapping of the PSS-05 phases to the ECSS E-40 processes

domain. Not least, it has a high level of criticality for the spacecraft, since failures can cause loss of the entire mission. Unlike aircraft systems, for example, no prototype flights can be made and the software has to work correctly as soon as the satellite arrives in orbit. Therefore, testing and qualifying the software to ensure it will work correctly 'first time' is a major challenge. Because of avionics, power and mass constraints, onboard software is designed with severe limitations on processing power and memory. However, it controls and handles most of the electrical systems and the interfaces to the onboard avionics, and therefore it belongs to the technically difficult class of 'hard real-time software', with many processes running in parallel and response requirements in the microsecond range. Moreover, since a large and ever-increasing proportion of mission and spacecraft functional requirements are implemented by onboard software, its specification and design is strongly coupled with the overall system-engineering activities of the mission.

This major expansion in spacecraft onboard software functionalities occurred after the 1980s, when PSS-05 was written. Hence, in producing the ECSS Software Standards, it was a priority to introduce and modernise the standards to take into account this evolution. Introduction of system-engineering processes and interfacing software-engineering activities to the overall system-engineering process are good examples of this. Another example is the adoption of life-cycle milestones such that software developments follow the same conventions as any other space-system development (SRR, PDR, CDR, etc.).

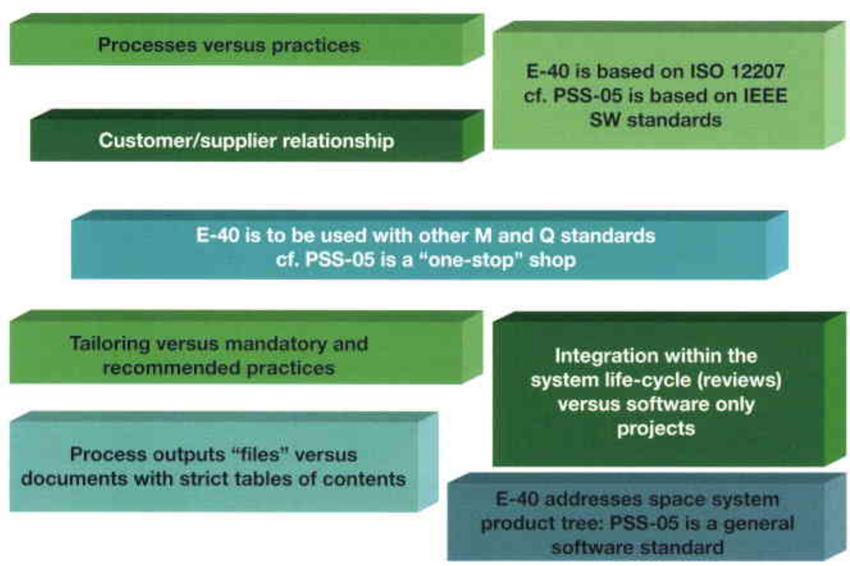


Figure 7. Comparison of the main features of PSS-05 and ECSS E-40

The first use of the ECSS Software Engineering standards was made as early as 1996. Since then, the combination of ECSS-E-40 and ECSS-Q-80 has been successfully applied to several tens of space projects, ranging from full-size satellite projects (in Space Science, Earth Observation, and Navigation) to smaller R&D activities in the areas of onboard software, Electrical Ground Support Equipment (EGSE), analysis tools and algorithm development. The transition to the new set of software-engineering standards has been successful, with no major problems vis-a-vis the ongoing space-segment developments.

Key factors in the successful introduction and application were:
- A strong commitment from the participating ECSS partners in producing very high quality standards and with internal commitments for the integration into their respective business processes.
- Training material and introduction courses both for those with previous experience with other standards and for those entering the space market for the first time.
- The ECSS tailoring possibility, allowing adaptation of the requirements to individual projects or domains.

Applying ECSS software standards to ground-segment projects at ESOC

The ESA Ground-Segment Software Engineering and Management Guide (ESA GS SEMG)

At ESOC, the bulk of ESA's ground-segment software is procured via frame contracts. Typically, there are several frame contractors in each discipline area (e.g. mission control systems, simulators, flight dynamics) and they compete for work as it arises. PSS-05 has been applied for all such software procurement and was made applicable in the relevant frame contracts. This led to a uniform approach to reviews and documentation across the various contracts in any given area. The desire was to continue this practice and avoid a situation in which different suppliers use different implementations of ECSS-E-40. This is particularly important for long-lived and complex infrastructures or generic software, where several different contractors may be involved.

Transition to the ECSS standards involves:
- using a process-based standard instead of a practice-based standard
- coping with the distribution of the ECSS standard over many documents (E40, Q-80, ECSS-M-) instead of one (PSS-05).

It was to ease these steps and provide a common implementation basis for the various frame contracts that the ESA Ground Segment Software Engineering and Management Guide (ESA GS SEMG) was written. This provides ECSS compliance in the form of a set of practices. It is written in a style similar to PSS-05, with a clear correspondence to the ECSS processes and requirements, and it covers all relevant ECSS standards in a single (multi-volume) document.

The SEMG is an *implementation guide*, applying the relevant ECSS standards to software development for ground segments. Implementation aspects include, for example, document templates and advice on how to perform the necessary work, in addition to the ECSS requirements. It is also an initial tailoring of the ECSS requirements for ground-segment software developments. The SEMG has removed some requirements that were not applicable to ground-segment development and has also introduced some missing ones, particularly in the areas of configuration management and software project management. Another example of the tailoring is the addition of the Software Requirements Review (SWRR) between SRR and PDR to provide a separate review of the software requirements and facilitate continuity with established practice.

An important feature of the ECSS software standards is that they may be tailored in accordance with customer needs and project or system characteristics. The GS SEMG can, therefore, be further tailored (corresponding in effect to a tailoring of the ECSS source standards). The Tailoring Template, also published by the BSSC, is a companion guide to the GS SEMG that provides guidance when introducing further tailoring. Specifically, it gives advice on the processes to be considered applicable within a given software-development project. It clarifies the principles upon which the tailoring process is based, allowing for the selection or waiving of some of the practices described in the Guide. It does not constitute a specific tailoring of the GS SEMG as such, and therefore should not be considered or referred to as contractually binding. However, a tailoring resulting from it could be made contractually binding.

The GS SEMG could be applied to any development of ground-segment software for a space mission. However, it is primarily intended for use in ground-segment software development at ESOC, where the GS SEMG will be referenced (i.e. made applicable) in procurement contracts.

The SEMG has three volumes:
- Part A: Software Engineering, covering ECSS-E-40
- Part B: Software Management, covering the ECSS-Q-80 and ECSS-M- series
- Part C: Document Templates.

Part A was the first one to be written and was the result of work carried out by a Working Group comprised of software engineers drawn from the ground-segment disciplines that develop and maintain software (simulations, mission-control systems, flight dynamics, ground-station information systems and spacecraft checkout).

The GS SEMG is based on new versions of ECSS-E-40 and ECSS-Q0-80, the so-called 'B' versions, which are currently under formal review within the ECSS. These do not differ in any principle respects from the ones currently on the ECSS Web site, but there are a large number of corrections and improvements.

The ESOC Quality Management System (QMS)
In November 1999, ESOC was the first ESA entity to be certified according to the ISO/IEC 9001 Quality Standard, following an 18-month preparatory phase. The rationale for this was that ESOC was providing services both to ESA projects and to external 'third party' projects, the latter following an ESA Council decision in 1998. ISO 9001 certification therefore increases ESOC's effectiveness and attractiveness as a supplier of services.

To support ISO 9001 certification, ESOC prepared a Quality Management System (QMS), which is a set of internal procedures and instructions defining implementation of work processes at ESOC and the associated responsibilities. It consists of:

- a Quality Manual describing top-level requirements on the management system

- a set of procedures and work instructions describing all of ESOC's business processes,

The procedures and work instructions are split up into different areas such as Ground Segment Management, Infrastructure, Configuration Management, and Procurement via Contracts. The QMS does not repeat the various technical and procedural standards that are used in ESOC's work, but rather refers to them as necessary.

At the time that the QMS was first written, all ESOC software projects were based on the PSS-05 standards, and so this was referenced in the QMS.

The transition process at ESOC
The transition process at ESOC involved reviewing the Quality Management System, identifying the changes needed to adapt to the new standard, making those changes, and formally re-issuing the QMS. A QMS revision team was defined, made up where possible of the original authors of the various QMS documents. A Workshop was held in April 2001 to introduce the team to the new standards, agree on the subset of documents that would require change, and make a plan for the phase-in of the new standard. The resulting plan foresaw a set of activities extending over one year, with an approved updated set of QMS documents by the second quarter of 2002, with a view to using the standard for new projects from that time onwards. Management approved this plan in May 2001.

The April 2001 Workshop determined that some 20 documents needed updating. In some cases the updates required were substantial, as with for example the procedure on 'Control of Software Procurement via Contract', where there were numerous references to PSS-05 had to be replaced. There were about half a dozen documents in this category. Other documents, such as all of the procedures relating to configuration control, needed only minor changes. A QMS Consistency Workshop was held in January 2002 to review the whole body of updated QMS documents and ensure that they were coherent.

In fact, the schedule was successfully maintained, with the formal issue of QMS documents taking place in early May 2002.

Training courses are planned, including a technical one for data system managers and technical officers in charge of defining and procuring software systems.

Conclusions
This article has outlined the new ECSS software-engineering standards and an intense set of activities within ESA to ensure their smooth introduction into the Agency's procurement of software for both the space and ground segments. The ECSS standards have been applied for some time to space-segment projects. The transition to ECSS standards for ground-segment projects at ESOC took place later, with the first projects beginning to use them via an implementation guide (the GS SEMG) this year. Indications are that the careful preparation and support has helped make the transition a smooth one.

The ESA Outlook Centre

– Identifying new opportunities for space-based solutions

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In November 2000, Carl Bildt, Jean Peyrelevade and Lothar Späth delivered their report entitled 'Towards a Space Agency for the European Union', more commonly known as the 'Wise Men's Report', to Antonio Rodota, ESA's Director General. For that report, they had independently analysed the evolution of the space sector in Europe and elsewhere in the World, thereby providing the Director General with some guidelines for taking the Agency forward into the new millennium.

Among their guidelines, the Wise Men identified the need for continuous progress in space technologies and for assessing the capabilities of competing ground-based solutions. In order to evaluate how ground-based technologies and solutions are evolving worldwide and to identify the fields requiring public investment for the development of competing or complementary space-based solutions, the establishment of a permanent 'observation post' within the Agency was recommended.

Introduction

Within the framework for the definition of its various programmes, particularly its application programmes, ESA already carries out 'technology-watch' activities aimed at identifying areas of possible development for space-based solutions. Those activities, although providing the information necessary to make programmatic choices, are often limited to the field of application in which they are generated and are driven primarily by industry, technologists and researchers, without a complementary vision based on an analysis of societal needs.

The need for such a complementary approach, and the advantages for ESA – and for the space community as a whole – of looking beyond the traditional 'space circles', suggested that we should evaluate the potential benefits that could accrue from the setting up of an 'observatory' for assessing the potential of space-based solutions compared to non-space-based ones, starting from a broad analysis of the needs and expectations of society for the next five to ten years. Hence the idea of establishing an ESA Outlook Centre as an additional and complementary instrument for the Agency and its stakeholders to take a look at the outside world and to bring to it the benefits of space-based solutions, has subsequently been evaluated.

'Space Serving European Citizens'

The ESA Council, meeting at Ministerial Level in Edinburgh last November, endorsed the Director General's proposal for ESA's policy and programmes, titled 'Space Serving European Citizens'. Coherent with the European Strategy for Space developed in co-operation with the European Commission and jointly endorsed by the ESA and European Union Ministers a year earlier, the Director General's proposal identified policies and programmes to be implemented by ESA to ensure better use of space technologies and solutions to the benefit of Europeans, whilst also contributing to the achievement of Europe's ambitions.

Space technologies and systems, although not always visible to the public at large, already play very important roles in existing services and applications (telecommunications, meteorology, in-car navigation, etc.), but how can we further improve their visibility, anticipate citizens' needs, and develop the breakthroughs required to meet them?

The existing approach adopted by publicly funded organisations operating in the space sector to identify fields of intervention can be largely characterised as a bottom-up approach, with programmes being elaborated based on current technological capabilities and on political trends and wills. It is clear that such a bottom-up approach, even if very efficient in improving European industry's capabilities and competitiveness in existing niche-markets for space-based solutions, might also run the risk of losing new opportunities and new markets.

In fact, simply acting as a follower of the evolution in ground-based technologies might bring about the non-development of breakthrough solutions and the non-investment of the public funds needed for creating and mastering new markets.

A new approach

The formulation of an overall picture of mankind's expectations will help us to understand where and how space-based solutions could play a significant role in solving problems, meeting latent demands, and implementing policies. This new top-down approach will help decision makers in Europe to identify fields in which public funds could be invested in anticipation of future user needs by developing gap-filler or breakthrough solutions, as well as by exploiting existing systems or technologies differently. It will therefore complement the existing bottom-up activities already in place at ESA as well as in other publicly funded organisations financing space projects. It will allow the Agency to meet the two-fold objective of:

- identifying the potential for space-based solutions directly linked to the users' expectations and needs, sometimes driving new technology developments and opening the door to breakthrough innovation
- changing the usual space-organisation perspective, which is currently often limited to the circle of space companies, opinion makers, scientists and researchers.

To implement such a top-down approach, a new 'Outlook Centre' is being established, within the Directorate of Strategy and External Relations, which will serve as a focal point. It will involve and potentially benefit all of the ESA Directorates, relying mainly (see below) on an internal network of staff drawn from the different Directorates both for its ideas and inputs and for communicating the Centre's findings and projections back into their own Directorates and structures.

Such a top-down approach in analysing and striving to meet the future demands of society is a typical feature of large industries operating in the manufacturing field. Pharmaceutical, automotive, aeronautical, telecommunications and energy companies all use this type of approach in planning their long-term investment in research and development geared to the production of innovative solutions. Such analyses often lead to the development of breakthrough products, the Renault Espace and the Airbus A380 being good examples. Such an effort should also be beneficial for the space sector, where long-term investments and planning are the norm. However, the market associated with space products is small and space-based solutions are still much more within the realm of governments than being driven by commercial demand. This is why those responsible for defining priorities and planning the development of future space solutions should take benefit from such a complementary approach and why ESA, as the body responsible for elaborating and implementing a long-term European space policy, has taken the initiative in implementing it within its structure.

Objectives and structure

The objectives that the ESA Outlook Centre will be pursuing, with a 5 to 10 year horizon, will include:

- anticipating and understanding the role of space-based solutions to meet society's expectations and needs
- evaluating the position of space-based versus non-space-based solutions vis-à-vis markets and society
- identifying space-based solutions already available to meet society's expectations and needs
- identifying specific space-based solutions to be developed and recommending investments in particular technology fields to stimulate breakthrough and innovation.

Although the Outlook Centre will be an ESA body, it will rely on a networking concept to involve different types of actors external to the Agency. This will provide a broader perspective in the analysis and improved sharing of the results with communities that are not focusing solely on space-related activities. Different parties will be involved depending on the particular process being used in implementing the Outlook Centre objectives, and they will interface with ESA's staff through a special body, namely the ESA Outlook Committee (EOC), which will be responsible of the management of the Centre itself.

The Director General, following recommendations from all ESA Directorates willing to join the process, will nominate the EOC members. The Director General will also nominate the EOC's chairperson, whose duties will include representing the Agency with third parties involved in the Outlook Centre process, convening and chairing meetings of the EOC, submitting agendas and items to be discussed, and producing analyses and reports. The chairman will be supported by a small team to assist in the organisation and management of the tasks relevant to the timely execution of the implementation process.

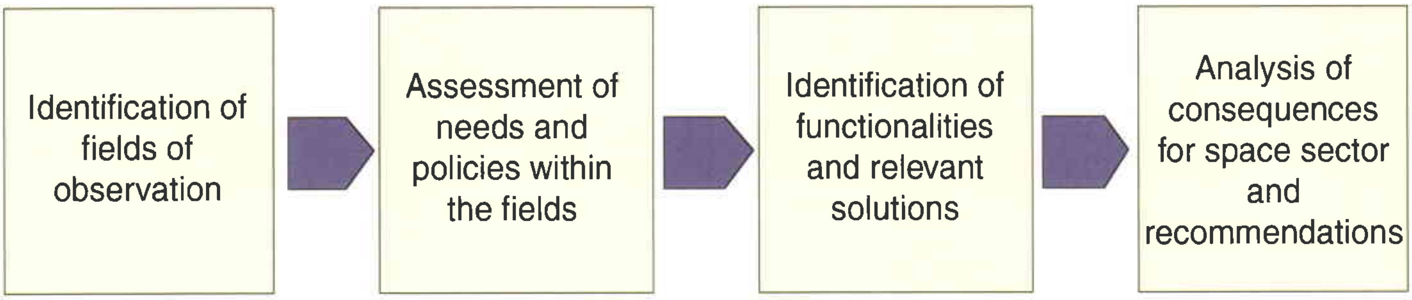


Figure 1. The process blocks

The process

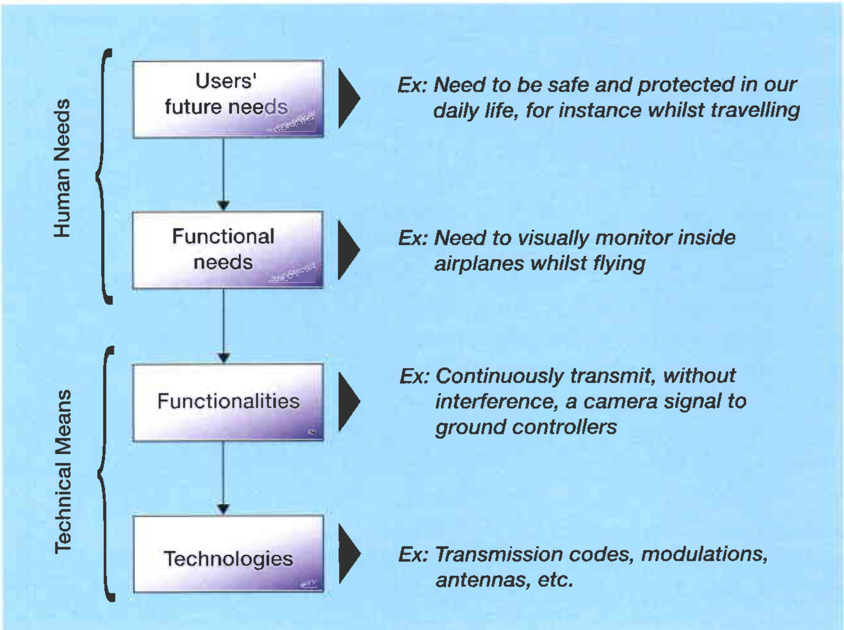
The process for achieving the objectives set for the ESA Outlook Centre can be divided into four main blocks (Fig. 1):

Block 1 – Identification of field(s) of observation and associated themes

Starting the top-down approach requires an analysis of society's needs and expectations by selecting one or more general fields of investigation. Such fields might encompass several analysis themes relevant to the development of innovative solutions and will be selected on the basis of analyses performed by external bodies (research centres and institutes) typically involved in such exploratory activities. The aim is to clearly identify areas in which society and future user communities will need new technologies and innovative technical solutions.

Typical fields for investigation include the environment, health, security, Earth resources, etc., each of which might generate several themes for analysis. The identification and selection process will rely exclusively on studies already performed by external bodies in Europe. The Outlook Centre will therefore federate a network of selected institutes and research centres and co-operate with them, on the basis of their already available results, to select appropriate analysis themes.

Figure 2. The process logic



Block 2 – Assessment of society's needs and expectations re the selected themes

Once the domains/areas to be analysed have been selected, the Outlook Centre will proceed to assess society's needs and expectations for each of them. This part of the process will require close co-operation with selected partners, in order to map their analysis results into the Outlook Centre's logic and goals.

The assessment will be based on two different courses of action:

- Identification of needs and expectations coming directly from society, considering the ongoing evolution in the citizens' daily lives, their lifestyles and habits, their working methods, as well as the changes in human relationships.
- Analysis of measures already undertaken or planned by institutions and governments to take into account society's evolution, i.e. policies and regulations, international agreements, and any other actions falling within the framework of the selected theme.

The combination of the two approaches will provide the Outlook Centre with a comprehensive picture of society's needs and expectations for the next 5 to 10 years.

Block 3 – Identification of functional needs, functionalities and associated solutions (space or non-space)

A further selection is necessary in the process to identify, within the general expectations and needs, the kinds of functionalities and associated solutions that may be required by society (and therefore also by commercial markets) in the future. The Outlook Centre then needs, again in co-operation with external parties, to translate these requirements into practical functionalities according to the process logic depicted in Figure 2. Such a delicate translation will lead to the identification of very specific areas where further progress is required, independent of the type of technological solution adopted.

At this point, the Outlook Centre will have at its disposal a comprehensive catalogue of areas in which space-based solutions could play a role.

Block 4 – Analysis of the consequences for the space sector

The final block of the process allows the Outlook Centre to analyse the added-value of space-based solutions in each area in which new or enhanced functionalities are required to meet society's expectations and needs. In this part of the process the Centre will co-operate with non-space-based industries and operators to identify the real opportunities for space-based solutions, as gap fillers, breakthroughs or simply complementary solutions with respect to other options. This analysis will also require the taking into account of possible market stakes associated with the development or use of space-based solutions.

Where space-based solutions are found to play a role in providing the required functionalities, the consequences for the space sector could be of two types:

(a) Where technologies to implement the identified solution have already been developed, validation and demonstration activities should immediately be planned and initiated.

(b) Where such technologies are not yet available, new or additional R&D activities should be planned in order to develop them and make them available to markets and/or public entities when the need is expected to materialise.

The process should run continuously, with two different duty cycles:

- Blocks 1 and 2, concerning society's requirements for the next 5 - 10 years in selected areas, could be updated every 18 to 24 months, being linked to the comparatively slow evolution in our lifestyles, habits, and working practices.

- Blocks 3 and 4, concerning the solutions to the society's requirements, may need a shorter duty cycle of 6 to 8 months, in order to take into account the rapid evolution in technologies, particularly in sectors strongly connected with market demand (i.e. telecommunications and information technologies).

The parties

As the Outlook Centre is intended to monitor society's current and future needs and fulfil them by widening the circle of application for space technologies, extensive and fruitful co-operation with external parties is an essential part of the process. The accuracy and validity of many of the analyses to be performed will depend directly on the availability and quality of the information coming from external sources. The process is entirely founded on the perspective and foresight analysis being performed in Europe by institutes and research centres, both public and private. Special agreements and arrangements will be drawn up with such bodies based on two main principles: partnership and networking.

A partnership model will be established with publicly funded European organisations, be it at European or national level, on a mutual-benefit basis, with no exchange of funds between the Outlook Centre and external participants foreseen. The contributions from external parties will consist of the provision of existing analyses and, possibly, adapting them to meet the Outlook Centre's needs. In return, the research institutes participating in the process will have access to the Centre's findings. As far as private centres are concerned, the Agency will seek to establish a suitable partnership agreement on a case-by-case basis, depending on the scale, capabilities and interests of the party concerned.

The second principle on which agreements with third parties will be based is networking. This implies that each actor permanently involved in one or more of the process blocks already described will be included in a virtual network with both the Agency and the other parties, to facilitate the maximum exchange and sharing of information.

Based on the above logic, three different kinds of partners for the ESA Outlook Centre are envisaged:

(a) One public institute performing foresight analyses at European level, itself the co-ordinator of a network of partners used to working together and producing analyses in different fields. This party will be a 'privileged partner' of the ESA Outlook Centre, being involved from the outset in the identification and selection of study fields and their associated analysis themes. Preferably an institute belonging to the European Union, it will partner ESA in the execution of the process, possibly also being associated with the EOC.

(b) Public or private institutes, which may or may not already be connected with the 'privileged partner', performing perspective and foresight studies on specific subjects or themes. These parties could be associated on either a mutual-benefit or a contract basis. They will share in the Outlook Centre's results according to the agreement regulating their association, and their participation will in principle be limited to Blocks 2 and 3.

(c) Associations of non-space-based industries and/or operators, to support the Outlook Centre with their points of view and to enhance synergies between the space and non-space worlds. Those associations will be involved on a case-by-case basis in Workshops organised during the execution of Blocks 3 and 4.

The pilot project

The ESA Outlook Centre's concept, its organisation within the Agency, the process for regulating it and the partners to be associated with it, have been studied and defined. Although many industries operating in high-technology domains requiring long-term investment, such as energy, telecommunications, transport or pharmaceutics, commonly apply a similar top-down approach to develop future products and the technologies supporting them, the processes implemented are usually confidential, making it difficult to understand exactly how they work in practice. Hence, before launching the Outlook Centre as a permanent ESA facility, the entire process must be thoroughly evaluated. A pilot project is therefore needed to benchmark the capabilities of the centre and its benefits for the Agency and its stakeholders.

The pilot project will last up to 12 months and its scope will be limited to the analysis of a restricted number of themes derived from a single field of observation. It will, nevertheless, allow ESA to establish the EOC, to select and find an agreement with the 'privileged partner', to identify and secure the participation of third parties according to the criteria mentioned earlier, to verify the networking concept both internally and externally with third parties, and to evaluate the cost/benefit ratio of the structure vis-à-vis other new ESA initiatives and programmes.

All ESA Directorates have been invited to participate in the Outlook Centre and to join the EOC. The Directorate of Strategy and External Relations and the Directorate of Industrial Matters and Technology Programmes are expected to play very specific roles, in the strategic planning of activities and in the implementation of recommendations concerning new technology developments, respectively.

Once the EOC has been established, the pilot project will start on the basis of the following tasks:

Task 1 – Identification and association of a privileged partner, possibly in the EU framework.

Task 2 – Identification of one observation field and associated themes, and the identification and association of relevant experts from third parties.

Task 3 – Collection of data from experts and its analysis.

Task 4 – Identification of technical functions and analysis of associated solutions and market stakes.

Task 5 – Analysis of the scope for existing and future space-based solutions and the identification of future actions to be recommended.

Task 6 – Outlook Centre management.

ESA's Management Board will continuously monitor the activities of the Centre. One or more internal workshops are foreseen to stimulate technical staff working in the relevant ESA Directorates to provide inputs and suggestions to be analysed within the Outlook Centre framework (i.e. with third parties).

The results and recommendations from the pilot project will be summarised in a final report to be submitted to the Director General and to the Management Board. A final workshop involving the privileged partner as well as all parties concerned and the ESA stakeholders, is also envisaged.

Conclusions

The idea of establishing a permanent observatory as recommended in the Wise Men's report has been carefully evaluated by the Agency. That evaluation has led to the conclusion that a new instrument is necessary to complement the bottom-up approach traditionally adopted by ESA and by other public actors involved in space-related activities to identify future developments.

ESA's response in the form of the new Outlook Centre to gather, through the implementation of a networking concept, competencies and capabilities within the Agency itself and from communities external to the space sector, will provide ESA and its Member States with the means for identifying new opportunities for space-based solutions, thereby complementing the bottom-up activities already in place.

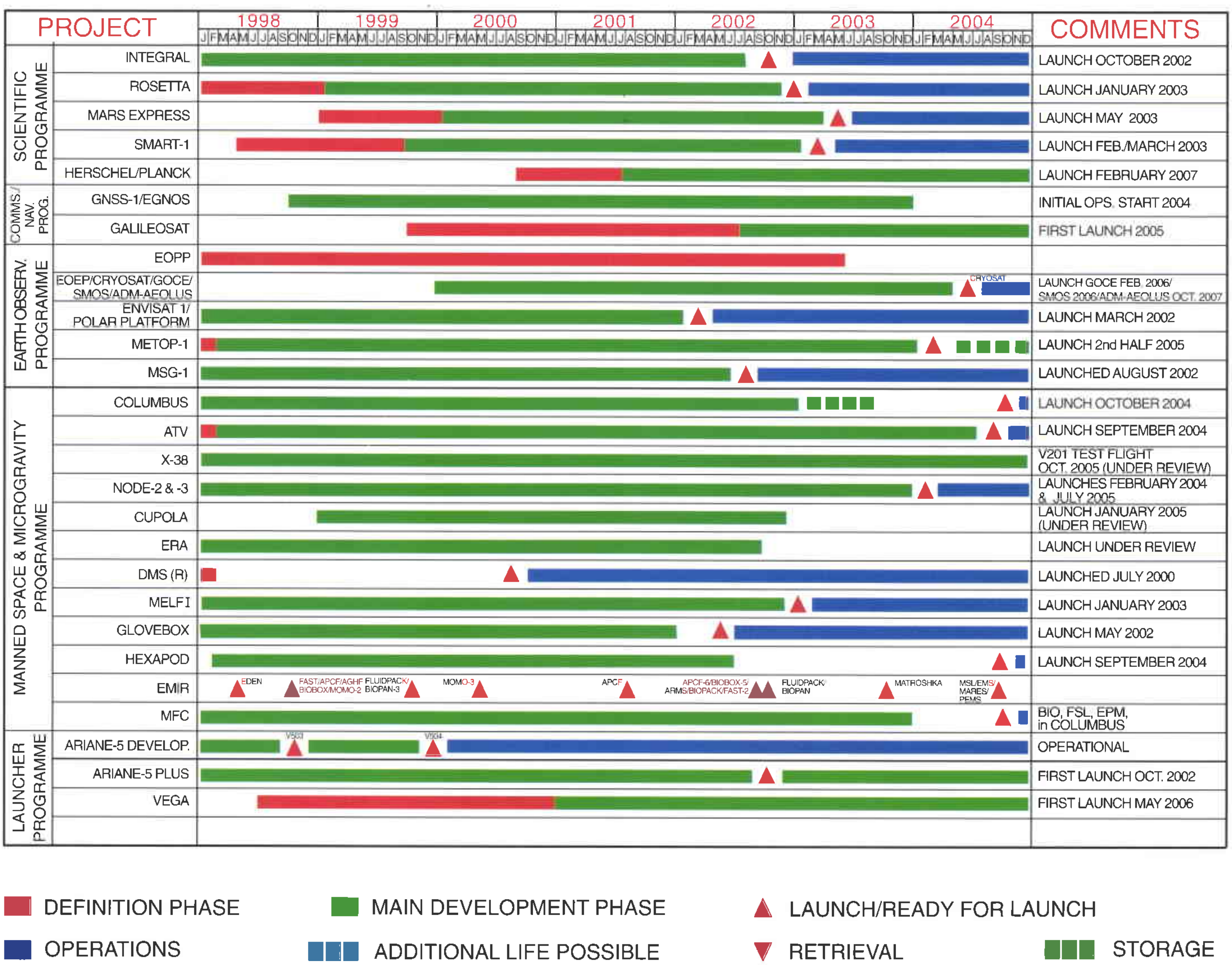
The Outlook Centre will be initiated as a pilot project lasting up to one year and focusing only on a few carefully selected themes of investigation. A hopefully successful outcome to the pilot project will ultimately establish the Outlook Centre as a permanent means of supporting Europe's decision-making in the space field. esa

Programmes under Development and Operations

(status end-June 2002)

In Orbit

Under Development



ISO

Around 100 astronomers from thirteen countries discussed the latest discoveries of ESA's Infrared Space Observatory (ISO) at the conference titled 'Exploiting the ISO Data Archive – Infrared Astronomy in the Internet Age', organised by the ISO Data Centre (Villafranca, Spain. The aim of this meeting held on 24-27 June 2002 in Siguenza, Spain, was to further promote the scientific exploitation of the ISO Data Archive.

The Horsehead Nebula, NGC 2023, as seen, on the right, by ESA's Infrared Space Observatory (ISO)

Exciting new results were presented in all fields of astronomy, showing that the exploitation of ISO data continues to be very productive. Many new projects were reported involving all kinds of observational modes. Special emphasis was given to projects involving large data sets and/or systematic data reduction, or any project making use of the data with a different purpose than that planned in the original proposal. It was confirmed that significant effort is required on the modelling and laboratory work to interpret the so far mostly unexplored wavelength range of 2-200 microns. The good position of the ISO archive in the framework of the international Astronomical Virtual Observatories was evidenced in a dedicated session.

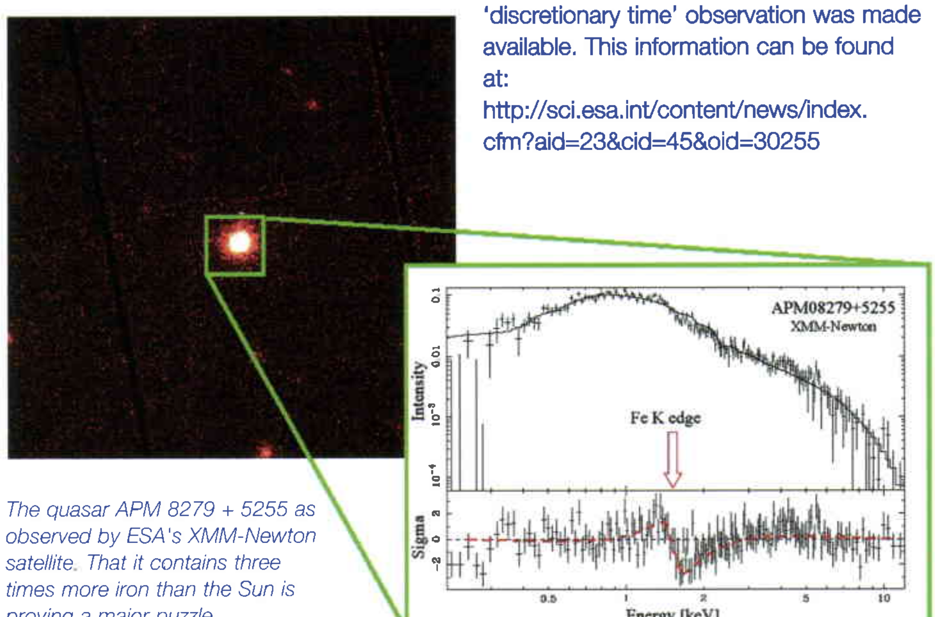
The conference had several positive effects: it stimulated researchers in their on-going projects to have results ready for the conference, it motivated people to think about the potential of ISO data and to realise what new studies could be undertaken, and it triggered new collaborations between teams and individuals thanks to the many opportunities for discussion, which ensured a lively scientific atmosphere.

ISO has so far resulted in more than 860 papers in the refereed literature, impacting all areas of astronomy. The ISO Data Archive has been populated with the last version of the automated Off-Line Processing pipeline, and the final version of a five-volume handbook is being released, giving a thorough description about the mission, its products and the associated calibration. A direct download capability has been introduced in the latest version 5.2.

ISO is now in its Active Archive Phase, lasting until end-2006, which will consolidate the success of the mission. During this phase, the Archive will continue to be improved with new data and information being ingested. Major tasks are: stimulating systematic expert data reduction and capturing the resulting data products into the Archive; tracking of refereed ISO publications and incorporating this information; ingestion of new ISO catalogues and atlases; continuing the process of increasing the interoperability of archives by linking to other data sets; and maintaining the ISO Archive, especially the user interface to maximise its usefulness and ease of use.

XMM-Newton

XMM-Newton operations continue to run smoothly. Solar activity has been minimal and very little science time was lost due to this.



The quasar APM 8279 + 5255 as observed by ESA's XMM-Newton satellite. That it contains three times more iron than the Sun is proving a major puzzle

Investigations to operate the X-ray detectors on-board XMM-Newton at –120°C, instead of the current –90°C, have started. The purpose of lowering the operating temperature of the X-ray detectors is to ameliorate some of the radiation-damage effects caused by spending over 2.5 years in space.

Preparations for the next eclipse season, in August/September 2002, have started. In between the autumn 2002 and spring 2003 eclipse seasons, an orbit-maintenance manoeuvre will be needed to ensure proper visibility of the XMM-Newton observatory from the ground stations.

The results of a very successful, so-called 'discretionary time' observation was made available. This information can be found at:
http://sci.esa.int/content/news/index.cfm?aid=23&cid=45&oid=30255

The story, which was also covered by CNN, describes an XMM-Newton result that may indicate that the Universe is older than so far believed.

XMM data processing and data shipment is proceeding nominally. Currently 1911 observation sequences have been executed, and the data for 1820 of these have been shipped.

The XMM-Newton Science Archive (XSA) has been released, allowing external observers to retrieve public, as well as proprietary data. The XSA is a very successful re-use of the software developed for the ISO Data Archive (IDA). The XSA can be found at:

http://xmm.vilspa.esa.es/xsa.

By end-June, some 160 papers based on XMM-Newton data had been published in the refereed literature, with quite some papers describing ground-breaking discoveries in X-ray astrophysics.

Artemis

During the last three months, the raising of Artemis's orbital altitude has continued, using its ion-thruster engines. Artemis has already been boosted by more than 1500 km from its parking orbit at 31 000 km altitude. Some problems with the ion thrusters on the south-facing side of the satellite mean that the orbit raising is presently being performed using only one thruster on the north side. This provides an altitude increment of about 15 km per day. As Artemis must climb another 3000 km, it will arrive at its nominal geostationary position only at the beginning of 2003.

The whole orbit-raising manoeuvre, involving a total altitude increment of 4500 km, will consume not more than 17 kg of ion-thruster fuel (xenon gas). This is serving as a perfect demonstration of the capabilities and high efficiency of the novel electrical-propulsion system carried by Artemis.

The satellite itself continues to show very robust behaviour. Not only are the nominal operations being performed fully satisfactorily, but it is also proving capable of sustaining previously unthought of manoeuvres in support of the orbit-raising activities. This demonstrates both the flexibility of Artemis's design and the excellent skills of the spacecraft's designers and operators.

Integral

The Integral spacecraft has now successfully completed the environmental test campaign in the ESTEC facilities in Noordwijk (NL). The final test of the campaign, the thermal-vacuum and thermal-balance test, passed without major problems. Subsequent functional verification tests demonstrated that the satellite is fully functional after the harsh test campaign and therefore ready to perform its scientific mission.

Based on the results of all various tests performed and the contents of the Integral technical data package, the Flight Acceptance Review resulted in the spacecraft being declared ready for shipment to the launch site. The Instrument Flight Acceptance Review had already previously concluded that the scientific payload was ready to fly. The plan is to ship the spacecraft and all the necessary ground-segment equipment to the Baikonur Cosmodrome in August, for a launch in October 2002.

The Launch Facilities Acceptance Review has also been completed and the conclusion was that the launch facilities are ready for the Integral launch campaign. The production of the Proton launcher system for Integral is also proceeding according to the agreed master schedule.

The last System Validation Test and End-to-End Test involving the spacecraft and the entire ground segment have been successfully completed. The Integal ground segment consists of the Science Operations Centre at ESTEC in Noordwijk (NL), the Mission Operations Centre at ESOC in Darmstadt (D) and the Science Data Centre in Geneva (CH). The Ground Segment Readiness Review has also been successfully completed.

Integral undergoing mass-properties testing at the end of the environmental test campaign at ESTEC in Noordwijk (NL)

Rosetta

The Rosetta flight-model spacecraft has successfully completed its environmental test campaign. It has undergone thermal-vacuum, acoustic, vibration and EMC testing, the latter finishing in June 2002. During July, some refurbishment is taking place, which will be followed in August by the final functional testing before shipment to Kourou (Fr. Guiana) in September. All subsystems are working nominally and the final on-board software that will be used for the launch and the commissioning phase is frozen. The electrical qualification model programme has been continuing in parallel to check out all of the autonomy and failure-recovery actions and to verify the on-board control procedures.

The Flight Acceptance Review (FAR) process for the proto-flight model spacecraft before shipment to the launch site has commenced.

Several of the scientific payload's detectors have been exchanged during the refurbishment activities and now a fully optimised and calibrated set of experiments are integrated. All payload elements have successfully passed their Experiment Flight Operations Reviews (EFORs).

The Lander is also being refurbished at ESTEC in Noordwijk (NL), with the final integration onto the Orbiter scheduled for mid-August. The Landing Gear Working Group has confirmed that the baseline landing gear, which has now been completely qualified, is acceptable for flight and so it will be mounted during this period.

The ground segment's development is nearing completion. The New Norcia ground station has already been used for ranging measurements with a spacecraft already in orbit and will be handed over for pre-launch preparations in August. Various test campaigns have been performed commanding the flight spacecraft from ESOC in Darmstadt (D).

Final preparations for the launch campaign are in progress, in order to receive the first shipment of ground support equipment in Kourou in early September. The manufacture and qualification of the Rosetta launch vehicle are proceeding according to plan.

The Rosetta flight spacecraft on the vibration shaker at ESTEC in May 2002

In summary, the risk on all outstanding items has considerably reduced over the last few months and everything is fully in progress for launch in mid-January 2003.

Mars Express

The Mars Express spacecraft is nearing completion, as the last units are being integrated and tested. Al experiment units are now mounted and the last flight unit to be integrated is the FM1 transponder, which has recently been delivered. Integrated system testing will commence at the beginning of August and the first Ground System Verification Test will take place shortly thereafter.

Arrival of the spacecraft at the environmental facilities in Toulouse is planned for 23 August, in order to begin the thermal-balance and thermal-vacuum testing in early-September. The spacecraft will remain in the Intespace test facilities until all of the system environmental tests (thermal, vibration, acoustic and EMC) are completed by the end of the year.

The spacecraft launch-vehicle adaptor is presently in Russia for integration checks with the Soyuz Fregat upper stage.

Following the tragic accident at the Baikonur launch facilities, a team of Starsem personnel have visited the site and are now working to restore the Mars Express integration facilities to 'flight status' in time for the spacecraft's arrival at the end of February 2003.

SMART-1

Spacecraft

The last three months have seen the assembly, integration and testing of the spacecraft flight-model units. The spacecraft is now almost entirely integrated. The system and power-control and distribution unit of the electronics subsystem are still represented by qualification/spare units, but all of the others are flight models. The on-board software is undergoing detailed verification testing, but a qualification version has been released. This version is presently being used to run the System Functional and Performance Tests (SFPT) to verify system hardware-software compatibility. The System Validation Tests, which will test end-to-end the commanding and telemetry functions from the Mission Control System at ESOC to the spacecraft, have also begun.

The spacecraft is currently being tested in the Saab Ericsson Space premises in Linköping (S), but will be moved to ESTEC in Noordwijk (NL) at the end of July, where it will complete the SFPT and will undergo environmental acceptance testing (vibro-acoustic, thermal vacuum and EMC). The current plan foresees the Flight Acceptance Review taking place in December 2002.

Payload
All of the payload instrument flight models have been integrated and tested on the spacecraft except KaTE, which will be integrated in early August. Some instruments have been dismounted after the test and shipped back to the responsible institutes for final calibration, and will be re-integrated on the spacecraft before the environmental tests.

Electric propulsion
The various flight-model components of the electric propulsion subsystem have been successfully integrated and tested on the spacecraft, except for the pressure regulator electronic card, which has to be integrated into the system unit, and the flight-model thruster, which can only be operated in vacuum conditions. The electric-propulsion end-to-end test will be performed in a specially equipped vacuum chamber (HBF3) at ESTEC in November. The engine will be turned on inside the chamber and its main functions will be verified.

Operations
The Ground Segment Implementation Review was successfully held in the spring. The testing phase is now in progress, both for the Mission Operations Centre at ESOC and the Science and Technology Operations Coordination at ESTEC.

Launcher
Arianespace has announced a flight opportunity for SMART-1 in the February-March 2003 time frame aboard an Ariane-5 vehicle, shared with a telecommunications satellite.

Herschel/Planck

The procurement activities for the Herschel and Planck spacecraft by the Prime Contractor and two core team members, Astrium GmbH and Alenia Spazio, dominated the activities in spring of this year. The completion of these activities and the finalisation of the industrial consortium for the overall development will be take place late this year.

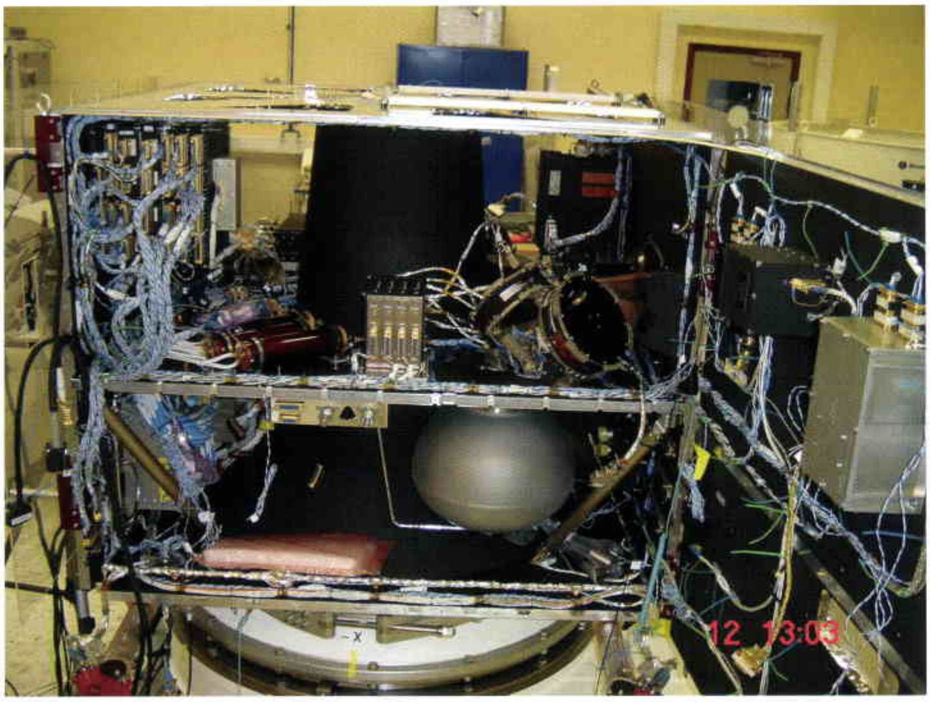
The Herschel/Planck Senior Procurement Board (SPB) has met twice during this period and gave authorisation to enter negotiation with companies that had provided proposals for Invitations to Tender (ITTs) in these two successive batches. The most important procurements considered in this period included the Attitude Control and Measurement Subsystem (ACMS) and a number of core avionics units. By the end of the three-month reporting period, about 40% of the total number of procurement items had been authorised, adding up to nearly two thirds of their total contractual value.

The activities on the baseline system and module designs continued, enhancing the maturity of the designs in preparation of the forthcoming Preliminary Design Review (PDR). The data-package delivery for this second major review in the Herschel/Planck spacecraft development effort takes place 2 July. The review will be conducted throughout the summer period and completed by a Review Board meeting in early October. Technically the most critical parameter for the spacecraft design remains the overall system mass.

The Herschel Telescope, developed under direct ESA contract by Astrium SAS, successfully passed its Critical Design Review (CDR) in May 2002. This review gave the go-ahead to start the manufacturing of the silicon-carbide primary-mirror petals. The Planck reflectors, under development at Astrium GmbH (outside the spacecraft contract with Alcatel and via a common contract with ESA and the Danish Space Research Institute) had its Critical Design Review in June and was equally successful. Both developments are proceeding according to plan.

The interfaces and contacts with the launch provider (Arianespace) further matured during this period and resulted in an updated understanding of the baseline.

Regarding the payloads of the two spacecraft, the defined plan of action to establish a clear technical baseline for the forthcoming PDR was implemented, involving significant effort on all sides. This goal was achieved and the remaining



Interior of the SMART-1 spacecraft

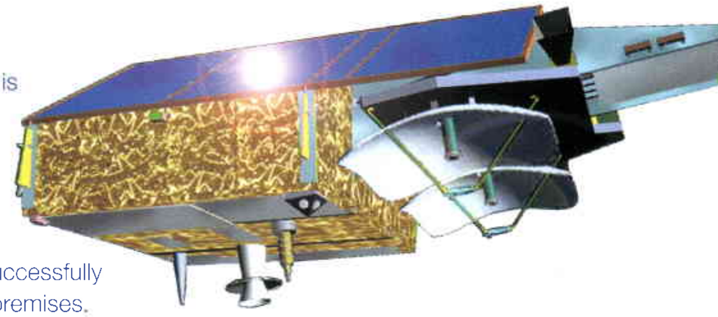
open points in the definition of instrument interfaces to the spacecraft were settled. Delays in the instrument development work, approaching manufacturing of the qualification models, led to new delivery dates. Industry fortunately found ways to modify the module and spacecraft qualification and acceptance test sequences such that the delays could be accommodated without impacting the launch date in February 2007.

Regarding the preparation of the scientific operations, the provision and review of the Science Implementation Plans for Herschel and Planck is running according to plan. Similarly for the Mission Operations Centre's preparation, a Customer Requirements Review was successfully completed on the 10 April at ESOC and the Mission Implementation Requirements Document was formally signed. The subsequent Mission Implementation Plan was released by ESOC in June.

At the meeting of the Science Programme Committee (SPC) held on 22-23 May 2002 in Andoya, Norway, the Executive's proposal to include the Eddington mission within the product and procurement cycle for Herschel/Planck was approved. Eddington, which will use an identical space bus to that of Herschel/Planck, will be integrated into the existing ESA Herschel/Planck project structure. The activities to establish the details of the implementation scenario for Eddington started shortly thereafter.

CryoSat

The CryoSat project is progressing well, within Phase-C/D. The engineering model of the onboard computer (CDMU) has been successfully tested at Laben's(I) premises. Concerning the radar altimeter (SIRAL), the original design has been slightly modified to include a calibration loop that will be able to provide, during flight, an increased accuracy of the SAR interferometric mode. Most of the industrial partners of Astrium GmbH, the Prime Contractor for the Space Segment, are now ready to start manufacturing the various equipment items for the flight model.



Artist's impression of the CryoSat spacecraft

Following evaluation of the offers received in April 2002, it has been decided that CryoSat will be launched by Eurockot from Plesetsk Cosmodrome in Russia.

The development of the CryoSat ground segment is going according to plan and the first review of the Instrument Processing Facility, limited to Level-1b products, has been successfully completed. The development of algorithms to derive CryoSat Level-2 products has been initiated.

More than 30 offers have been received from some 13 countries to support the calibration and validation campaigns for CryoSat. Consolidation of these proposals is currently in progress.

GOCE

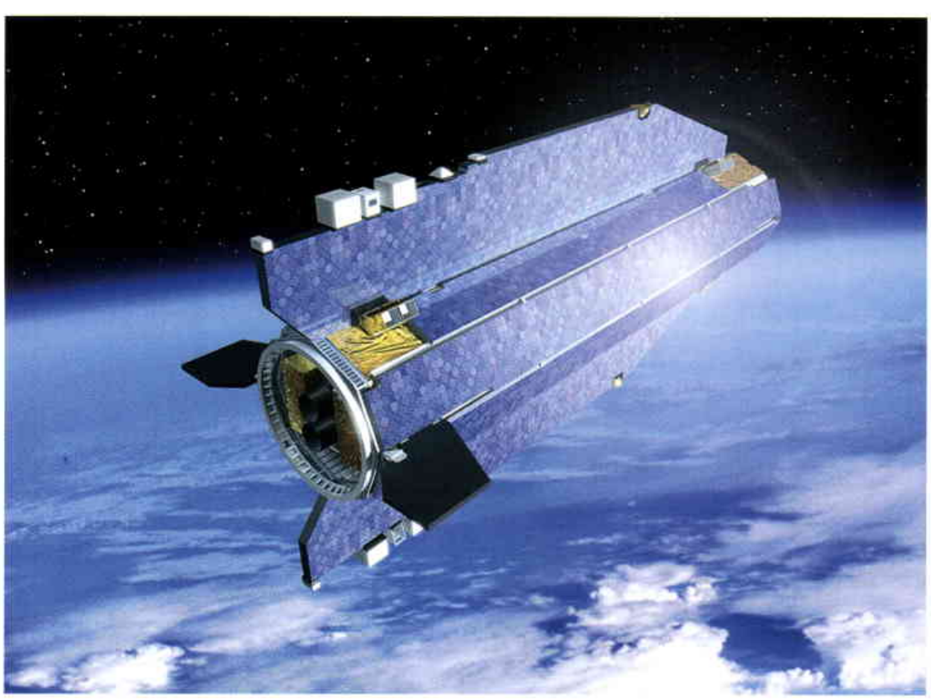
The GOCE space-segment development effort has achieved the last Phase-B milestone represented by the successful conclusion of the GOCE Preliminary Design Review (PDR) at the Board Meeting held on 9 April. The PDR Board concluded that the overall design of the GOCE space segment is sound and that no technical showstoppers have been identified.

Authorisation has been given to Alenia Spazio to proceed with the Phase-C/D activities.

The competitive-selection process for the various equipment suppliers is nearing completion, with the selection of the suppliers for the solar array and the micro propulsion assembly.

In the gradiometer development area, which is the most critical element in terms of the GOCE schedule, several solutions have been identified and are currently under discussion. In addition, dedicated tribological tests have been started for improving the capability of the accelerometers to withstand the launch vibration environment. Analysis and simulation campaigns have been initiated to consolidate the performance of the gradiometer in-flight calibration.

At satellite level, design rules and testing techniques are currently defined as proactive measures for detecting in the



Artist's impression of the GOCE spacecraft
Illustration: Pierre Carril

early equipment-development phase and thereby avoiding micro disturbances, which would have an adverse impact on GOCE's performance.

Preparations for the Ground Segment Requirements Review are progressing nominally towards the planned September 2002 date.

Envisat

The Envisat satellite was successfully launched on 1 March 2002, attained its final orbital position on 3 April, and is now orbiting in its assigned 35-day repeat cycle, 30 min ahead of ERS-2. Both satellites are controlled to fly over the same ground track with ± 1 km accuracy. The Service Module and all instruments are operating nominally, and all instrument modes have been used and very stable performances have been observed from all of them.

In the Flight Operations Segment (FOS), control of the key functions of the satellite service module and the related functions such as orbit maintenance continue to be nominal. The experience gained during the first months of commissioning has been reflected in an update of the Flight Control Procedures by the ESOC Flight Control Team. The FOS is now fully operational, with satisfactory performances to support the next phases of the mission.

The Payload Data Segment (PDS) has been operated to support the Switch-On Data Acquisition Phase (SODAP), the acquisition of the first images (from ASAR and MERIS), and the early activities of the Calibration/Validation Phase. The PDS is being operated in a so-called 'Kiruna-only' mission scenario, inducing a very high workload on the ground segment, due to the recovery of the full global mission (i.e. 14 orbits per day at the Kiruna station). The PDS performance was initially not found to be reliable enough to maintain the original planning for data-product delivery to users. Corrective actions are underway.

All installed instrument ground processors have been updated to reflect the specific characteristics observed early on in-orbit and the current instrument commissioning status. Good products should be available to users on a regular basis shortly.

The Italian island of Sicily as seen with Envisat's MERIS instrument

In the area of mission management, work is ongoing with distributor entities, and international-cooperation projects. Of the more than 600 Envisat Announcement of Opportunity (AO) projects, more than 200 are already in progress. Well over 100 Principal Investigators (PIs) have already started working within the various calibration and validation teams.

Envisat early results have already been presented in dedicated Envisat sessions at various large scientific symposia and at Earth Observation exploitation events (e.g. IGARSS'02, EUSAR, EGS, DUP and TESEO workshops). Material prepared for these events is available for further promotional use. A wide selection of Envisat images are available in an image gallery within the ESA web portal.

The Envisat Commissioning-Phase Review is foreseen to be held at ESTEC (NL) from 9 to 13 September 2002.

MetOp

The MetOp integration programme is continuing to plan, without major problems. A notable milestone was reached with the delivery, following the completion of its calibration campaign, of the first GOME-2 flight model.

Good progress has also been made on the first flight model of the GRAS instrument, whose electronic units should be completed in time for integration later this year. Some problems have been encountered with the antennas for this instrument, in terms of the quality of the metallisation and solutions for this are being identified.

Integration of the ASCAT flight instrument is proceeding to plan. A higher than anticipated sensitivity to cosmic-ray-induced single-event upsets has been detected in the switching front-end, which may impact the design of this unit. However, work-arounds are in place to safeguard the MetOp-1 schedule.

The IAST instrument's CDR has completed, with generally successful results. Concerns remain, however, about the instrument's ability to cope with the MetOp mechanical environment, and as far as its delivery schedule is concerned. This latter concern has been compounded by a recently discovered problem of cracking in the detectors.

Eumetsat's Polar System has now completed its Preliminary Design Review. The core ground segment has successfully passed its Critical Design Review, with good progress being evident since the Preliminary Design Review. An important milestone for the ground segment was achieved with the first delivery, from MetOp, of the Spacecraft simulator.

An in-house assessment of the feasibility of replacing the AVHRR on MetOp-3 with a new European imager has been conducted for the case where the AVHRR's use proves not to be viable. It is intended that this assessment will be complemented by focused industrial studies in the coming months. In parallel, within the framework of EOPP, preparations are in hand for the Phase-A study of a new imager, VIRI-M, aimed at fulfilling a supporting role to the IAST sounding mission.

Meteosat Second Generation

The first MSG spacecraft (MSG-1) is ready for its Ariane-5 launch, which is now scheduled for 27 August (Flight V-153). All the tests planned have been performed successfully. The predicted shock levels are now compatible with the MSG qualification designed for Ariane-4, thanks to the introduction of a mass attenuator in addition to the shock absorber used for Envisat. The late battery problem with the GERB instrument has been overcome by means of an operational solution. Following the launch delay from 13 to 27 August announced by Arianespace, a break of three weeks was introduced into the launch campaign in July. The launch rehearsals are being performed as planned by ESOC (D).
(see page 24 for news of launch)

ADM-Aeolus

The industrial contract for the satellite was kicked off on 1 July, as the result of an Invitation to Tender (ITT) issued in September 2001, and extensive negotiation of the resulting proposal. The contract foresees a launch in October 2007.

The fixed-price contract is for Phases-B, C, D and El of the satellite, together with some supporting equipment and services. The Phase-B has been kicked off with Astrium UK as Prime Contractor, Astrium France supplying the single instrument (ALADIN, a direct-detection doppler lidar), and Astrium Germany supplying platform equipment. Saab of Sweden will also provide data-handling support during Phase-B. Other subcontractors will be selected, in close consultation with ESA, during Phase-B, which is expected to last about 15 months.

MSG's arrival in Kourou, French Guiana

To measure global wind velocities throughout the Earth's atmosphere, the satellite will embark a solid-state laser producing ultraviolet light at 355 nm. Significant development work has already taken place on this laser. This work was reviewed by the satellite contractors and by ESA prior to the kick-off. The pulse output energy available from the lasers under development is not yet completely adequate for ALADIN. A number of alternative strategies are therefore being developed during the first four months of the Phase-B for dealing with this issue.

International Space Station

ISS Overall Assembly Sequence

Four assembly and logistic flights were made to the ISS in the second quarter of 2002, bringing the total number of flights to date to 29. The most recent additions are the centre segment of the 91 m station truss, attached to the US laboratory 'Destiny', and the Mobile Transporter, which allows the Station's robotic arm to ride along the truss to perform assembly and maintenance work. ESA astronaut Roberto Vittori was taken to the ISS onboard a Soyuz 'Taxi' flight. The fifth MPLM logistics flight carried ESA's Microgravity Science Glovebox (MSG), the first multi-user experiment facility for the ISS, and the fifth Expedition Crew to the Station. In addition, one Russian 'Progress' logistics flight has been flown.

Investigations are still ongoing as to the overall final content of the ISS, the so-called 'End State' configuration, which is under question due to the budgetary situation of NASA in the USA.

Columbus Laboratory
Integration of almost all the internal functional components of the Columbus flight unit is now complete, and the close-out plate of the starboard end-cone has been installed and wired up. The first functional system testing on the flight unit has been performed successfully, and system functional qualification testing on the electrical test model has continued.

Columbus Launch Barter

Nodes-2 and -3
The system-level modal-survey test has been successfully conducted and the integration of the Node-2 flight unit has been initiated. Integration of the very complicated active and passive docking mechanisms has also been initiated.

The Node-3 Critical Design Review (CDR) is planned for spring 2002, and preparations for this are now underway.

Crew Refrigerator / Freezer (RFR)
Preparatory activities for the qualification of the Refrigerator/Freezer in October are in progress.

Cryogenic Freezer (CRYOS)
Following the kick-off in February, activities are progressing as planned.

Cupola
Preparation for the system qualification vibro-acoustic test on the Cupola Structural Test Article (STA) has been completed and the STA has been shipped to the test site. Following completion of that activity, the STA will be delivered to NASA/JSC for use in crew training.

Manufacture of the flight-unit dome forgings, shutters, harness and window frames has been completed; the forgings are now undergoing machining.

Automated Transfer Vehicle (ATV)
All mechanical system qualification tests with the Structural/Thermal Model (STM) have been completed at ESTEC in Noordwijk, and the configuration has now been disassembled, with the pressurised Cargo Carrier being returned to the Contractor for refurbishment into a Crew Trainer, and the functional spacecraft being prepared for the thermal-vacuum test.

Tests on the avionics Electrical Test Model (ETM) are continuing and equipment CDRs have been completed without problems. The Stage-2 propulsion qualification test has been performed and the structural elements of the first flight model - christened 'Jules Verne' - are now being manufactured, with integration of the corresponding avionics bay also having started.

X-38/CRV and Applied Re-entry Technology (ART)
Work on the European contributions to the X-38 vehicle has continued and all European contributions to the X-38 vehicle will be completed in 2002. In the meantime, NASA has initiated a so-called 'graceful shut down' of the X-38 programme as part of their ISS cost-reduction exercise, and the Crew Return Vehicle procurement has been put in abeyance for the time being.

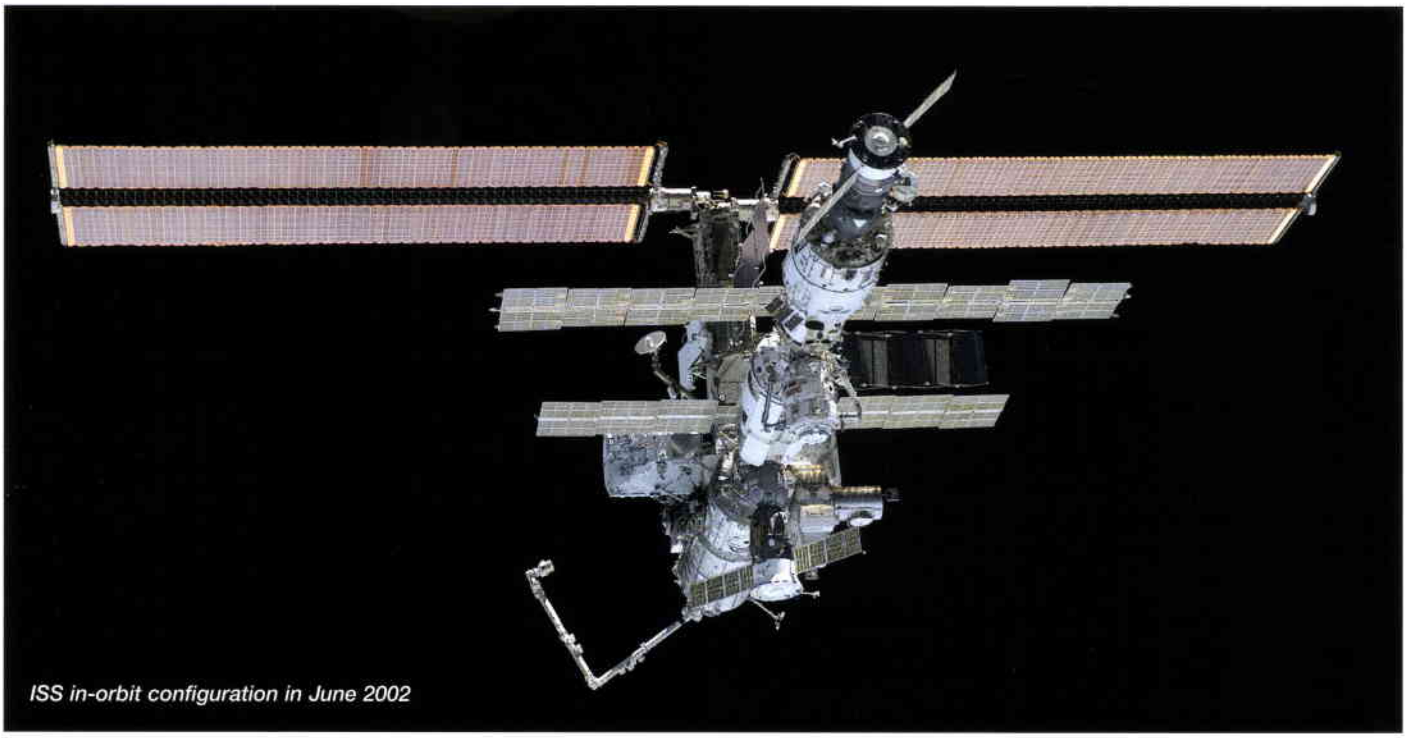
Whilst awaiting clarification on the final outcome of the project, activities related to generic technology developments for manned re-entry vehicles have been initiated at a low level.

Ground-segment development and operations preparation
The Preliminary Design Review (PDR) for the ATV Control Centre has been completed in May/June. The design and planning data will serve as the technical input for the Phase-C/D proposal to be submitted in September. The procurement of all subsystems for the Columbus Control Centre has been initiated. The system Phase-C/D proposal will be submitted in October.

The mechanical crew trainers for Columbus have been delivered to NASA and to the European Astronaut Centre (EAC) in Cologne. The implementation phase for the ATV crew training and simulation facility has started in June.

Utilisation

Preparation
The European Utilisation Board (EUB) met on 27 May and discussed the status of



ISS in-orbit configuration in June 2002

Space Station Utilisation and the NASA Research Maximisation and Prioritisation Task Force (ReMap), as well as the priorities regarding external payloads and the options under investigation by ESA.

Of the 44 Microgravity Applications Promotion (MAP) projects originally planned, 43 are now ongoing with some approaching first-phase completion.

Payloads and their integration
A NASA assessment has concluded that two ESA external payloads mounted on the ICC-Lite carrier could fly on the Columbus flight. The ICC-Lite is a non-deployable, cross-bay carrier, which may require adaptation to transport the ESA external payloads, instead of the originally planned Express Pallet System.

The PDR and Safety Review 0/1 for Solar/Expose have been successfully completed.

The Matroshka radiation-monitoring instrument for the Russian segment passed the Phase-0/1 safety review with NASA.

Phase-C/D for the European Drawer Rack (EDR) has been in progress since November 2000. A successful safety-panel review took place at NASA/JSC in April.

The Materials Science Glovebox (MSG) was successfully delivered to the Space Station in June and the Ground Unit (GU) was in the High Bay of the Erasmus User Centre at ESTEC for use during the F. de Winne Taxi-Flight experiment tests and training.

The MELFI –80 degC freezer flight unit (FU1) has been at NASA/KSC since late-March, where compatibility and post-shipment functional tests have been successfully performed. FU1 is manifested for launch on flight ULF1 in January 2003.

Qualification testing of the linear actuator for the Hexapod pointing system has been completed. Delivery to NASA is planned for November 2002.

The Global Transmission System (GTS) in-orbit checkout tests continued, as did the investigation of the cause of the transmission problems experienced.

Astronaut activities
Claudie Haigneré, the ESA Astronaut who flew to the ISS with the Andromède mission in October 2001, has been nominated 'Minister for Research and New Technologies' in the newly elected French Government.

Roberto Vittori became the third ESA astronaut to visit the ISS, as Soyuz Board Engineer on the 'Marco Polo' mission, which was launched from Baikonur on 25 April 2002. After the successful completion of the mission, the crew landed safely in Kazakhstan on 5 May.

Frank De Winne continued training in Star City for the 'Odissea' taxi flight sponsored by the Belgian Office for Scientific, Technical and Cultural Affairs (OSTC). Andre Kuipers resumed Basic Training at EAC and Star City in May and June.

The Advanced Training Readiness Review for Columbus Systems Training (first part), with the participation of ISS Partner and crew representatives, has been successfully concluded. The second part will take place in August to confirm readiness for the first ISS Advanced Training at EAC, which will be carried out in September 2002.

ESA astronauts and the EAC Crew Surgeon supported the first mission of CNES astronaut Philippe Perrin.

Early deliveries

Data Management System for the Russian Service Module (DMS-R)
The DMS-R is continuing to perform without problems. A single anomaly in the interface area between the ESA and Russian software, which occurred in February, has been corrected.

European Robotic Arm (ERA)
The ERA qualification programme at system level is in progress. The complexity of the Mission Preparation and Training Equipment has been a major contributing factor to the further delay of the Qualification and Acceptance Review to spring 2003.

The Russian Space Agency has proposed an alternative launch option for ERA to decouple this launch from the development and launch of a not-yet-available Russian element. A decision on this proposal should be taken by the end of year.

ISS Exploitation Programme
In line with the agreement with industry for a transitional approach towards implementing the industrial operations end-to-end service contract, the procurement of critical ATV components has been initiated. The RFQ for the production of seven ATVs for the exploitation phase has also been released.

For commercialisation, the mechanisms to implement the cooperation agreement with industry have been jointly established.

For the important task of promoting the image of the ISS, a number of non-space communication companies have responded to the ESA call for interest. The RFQ has been released and the contract should be initiated before the end of this year. The Canadian Space Agency is participating and providing additional funding.

The commercial blood-pressure-measurement project has been successfully performed during the taxi mission with the ESA astronaut Roberto Vittori.

Microgravity

Coordination discussions with the European Commission continued and ESA submitted two responses, one in life sciences and one in physical sciences, to the recent EC Call for Ideas for Integrated Projects.

Preparation of ESA's APCF, Biobox, ERISTO, FAST, ARMS and Biopack payloads for their July 2002 flight on STS-107 were completed. In June, however, NASA announced the grounding of the Shuttle fleet whilst investigations are carried-out into cracks in the liners of Shuttle fuel lines. This will seriously impact the STS-107 launch date.

All ESA facilities for the Foton M-1 Russian recoverable-capsule mission, scheduled for 15 October, have been completed and were in the process of being shipped.

Preparations for the March 2003 Maxus-5 sounding-rocket mission continued.

Development of various payloads for the ISS continued. NASA has announced a launch date of July 2004 for the European Modular Cultivation System (ECMS) biology facility, and it is now expected that the Expose facility for exobiology will be launched with Columbus. Delivery to NASA of the physiology instruments HGD/PFD and PEMS is nearing completion.

Development of the MARES (physiology) and Matroshka (radiation) facilities for the Russian module and the PCDF (proteins) facility for the European Drawer Rack (EDR) has continued.

Microgravity Facilities for Columbus (MFC)
The Biolab flight-model subsystem procurement and manufacturing has continued without major difficulties, at a level of 80%. For the Fluid Science Laboratory (FSL), the studies on the experiment containers started, and the crew review was successfully completed with ESA and NASA astronauts.

For the Material Science Laboratory (MSL) in the US Lab, the engineering-model tests started in June. The engineering-model functional test was successfully completed. Manufacture of the MSL flight model is 85% complete.

The CDR data package for the European Physiology Modules has been completed.

The Intermediate Design Review for the Electromagnetic Levitation Furnace in MSL (MSL-EML) was successfully held and significant progress was made in the definition of the system, the subsystems and the operational scenario.

Ariane-5 Plus

The second simulation of the launch chronology with the filling (MR) model of the ESC-A stage took place in April, with four synchronised sequences. The stage was completely filled and several operational sequences were run. The ground facilities systems and equipment showed good behaviours. Some complementary analysis and improvements to the stage's thermal protection were implemented before the third simulation, which took place in mid-June. It allowed some key procedural points to be investigated (e.g. the case of an aborted launch sequence), as well as the effectiveness of the improved thermal insulation of the tanks. The test results are currently being analysed; the insulation's improved thermal behaviour provided a significant improvement in the conditions for the liquid hydrogen and oxygen. Two additional MR chronology sequences are scheduled in the second half of July.

The acceptance of the Vulcain-2 engine for the first Ariane-5 ESC-A flight is still pending, awaiting a number of investigations and complementary tests concerning the qualification of the existing manufacturing standard of the liquid-oxygen turbo-pump. The date of the first Ariane-5 ESC-A flight (A517), which has been rescheduled for end-October 2002, remains to be confirmed.

Vega / P80

For the Vega small launcher's development, the Preliminary Design Reviews (PDRs) for the solid-rocket motors (Zefiro-23 and Zefiro-9), the inter-stages, and the fairing were completed in June. These reviews, covered by the initial activities contract, have implemented the design choices resulting from the System PDR at sub-system level. Meanwhile, the industrial proposal received at the end of April for the main development phase is being evaluated, including several clarification meetings with the Prime Contractor (ELV).

On the P80 side, the Preliminary Design Review final report has been submitted to the Review Board. Development work has continued with special emphasis on the actions resulting from the PDR Board's recommendations.

Launch base and ground facilities

The ELA-3 Control and Command Systems Qualification Commission meeting took place in April. The final report of the Technical Review Board on the UPG (Guiana solid-propellant plant) was presented in May, and an action plan coherent with the Commission's recommendations will be prepared. The Critical Design Review for the additional solid-propellant casting pit building equipment took place in June; the civil works for the building are progressing well and on schedule.

In the Vega Ground Segment area, activities have been concentrated on the preparation of the Preliminary Design Review, for which the kick-off meeting took place in June. On the contractual side, a Request for Quotation covering the Vega Ground Segment Technical Management, Engineering and Tests has been issued, in line with the Procurement Plan approved by ESA's Industrial Policy Committee (IPC). A proposal is expected by the end of July.

A new procedure concerning 'Ariane Assets Management' has been finalised and sent to all industrial partners, CNES and Arianespace at the beginning of May. The development of an electronic Ariane asset-management system has started with the definition of the functional specifications. The system will be made available on line to all industrial companies involved the Ariane programmes, with remote secure access to a Windows-based application through a central server located at ESA Headquarters. It will facilitate the management of the Ariane inventories by improving the exchange of data between the ground-facilities managers and ESA. The database will be the repository for all information on European ground infrastructure for Ariane.

esa

In Brief

From ESA Astronaut to Government Minister

Astronaut Claudie Haigneré has been nominated as Minister for Research and New Technologies in the French government.

After completing her PhD in neurosciences and a career at the French space agency, CNES, Claudie Haigneré joined the European Astronaut Corps in 1999.

She has taken part in two space missions with the Russians, 'Cassiopée' in August 1996 and 'Andromède' in October 2001. She was the first woman to qualify as a Soyuz Return Commander (July 1999), responsible for the three-person Soyuz capsule during a re-entry from space, and was the first European woman to visit the International Space Station (October 2001).

Claudie Haigneré

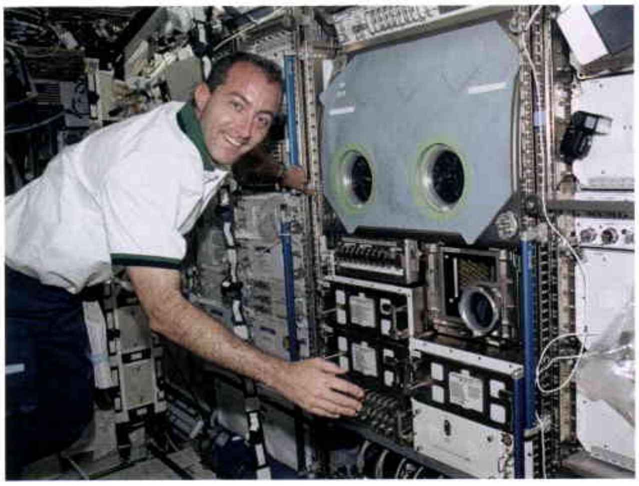
ESA's Director General, Antonio Rodotà, expressed delight at her appointment, commenting that:
"This appointment is an honour for the European Space Agency and puts Mrs Haigneré in a key position to shape the future of Europe's science and technology."

MSG installed in the ISS

On the morning of 6 June, ESA's Microgravity Science Glovebox (MSG) was successfully launched from Cape Canaveral inside the logistics module MPLM-Leonardo, aboard a US Space Shuttle mission to the International Space Station (STS-111UF2). The in-orbit commissioning phase was completed successfully, and the ISS crew has performed a first material-sciences experiment.

The MSG is the first European-provided research facility to have been launched to the ISS and the first to have completed the verification programme for this class of pay-loads, becoming the reference for the future development of ISS payloads. Astronauts will use it to perform a wide variety of materials, combustion, fluids and biotechnology experi-ments, as well as other investigations in the unique microgravity environment of the ISS.

Astronaut Philippe Perrin, STS-111 mission specialist, floats near the MSG in the Destiny laboratory on the ISS. (photo NASA)



It can also accommodate minor repairs and servicing of hardware requiring a controlled working environment. The facility offers users a wide range of innovative utilisation alternatives, from manual control by astronauts via laptop computers to fully automated and remote control from Earth (telescience). A permanent data exchange link with ground stations is also available.

The MSG will be used in the US Destiny Laboratory for a projected operational period of ten years.

ESA is planning to use the facility for European experiments. The first time MSG will be used by a European astronaut to perform European experiments will be during a Soyuz "taxi flight" mission in October 2002. ESA's Belgian astronaut Frank De Winne will perform four different experiments in the MSG, addressing the fields of protein crystallisation, zeolites crystallisation, combustion and fluid science.

The prime contractor for the development of the MSG is Astrium GmbH (D), with Bradford Engineering (NL), Verhaert Design and Development (B), ATOS (NL) and Laben (I) as subcontractors.

Swedish chair for ESA Council

Per Tegnér, currently Director General of the Swedish National Space Board, is the new Chairman of the ESA Council for the next two years (as from 1 July 2002).

Mr Tegnér was unanimously elected at the 159th meeting of the ESA Council, held at the Canadian Space Agency in Montreal on 12 and 13 June. He takes over from Mr Alain Bensoussan of France, whose term of office ended on 30 June 2002.

Per Tegnér, born on 22 April 1944, holds a Masters in Economics and worked for more than 25 years for the Swedish Ministry of Industry. In 1998 he was appointed Director General of the Swedish National Space Board and has been the Head of the Swedish Delegation to ESA since then.

ESA selects new Earth-Observation missions

For its second cycle of the Earth Explorer Opportunity Missions, ESA has recently selected three proposals to enter feasibility study: ACE+ , an Atmosphere and Climate-Explorer; EGPM, the European contribution to Global Precipitation Mission; and SWARM, a constellation of small satellites to study the dynamics of the Earth's magnetic field and its interactions with the Earth system.

The first Earth Explorer Opportunity Mission selection took place in 1999 and resulted in the selection of Cryosat and SMOS. Unlike the larger Earth Explorer Core Missions, which are ESA-led research missions, Opportunity Missions are smaller, have a greater degree of industrial involvement and are not necessarily ESA-led.

The three candidate Opportunity Missions recently selected will complement areas of research currently under development in the Earth Explorer programme. Once the feasibility studies are complete, two of the three missions will be retained for implementation, with the launch of the first envisaged for 2008.

SWARM: one of the three new Earth Explorer Opportunity Missions selected for Phase-A study

ACE+

The principal goal of ACE+ is to measure variations and changes in global atmospheric temperature and water vapour distribution and so provide valuable data for monitoring climate change. ACE+ will also be used to improve weather forecasting. The mission will use four satellites in orbits between 650 and 850 km altitude. Each will carry an L band receiver for GPS/Galileo sounding and a multi-frequency X-K band transmitter or receiver for satellite-to-satellite cross-link measurements.

EGPM

EGPM is a mission consisting of a single satellite in a Sun-synchronous, low Earth orbit and carries a precipitation microwave radiometer, which will provide global rainfall observations. It is an element of the joint NASA-NASDA GPM mission proposal, which comprises a 'core' satellite carrying a precipitation radar and a precipitation radiometer, and a number of smaller satellites with only a precipitation radiometer on each.

SWARM

The objective of the SWARM mission is to provide the best survey ever of the geomagnetic field and its temporal evolution, and gain new insights for improving our knowledge of the Earth's interior and climate. The SWARM concept consists of a constellation of four satellites in two different polar orbits between 400 and 550 km altitude. Each satellite will provide high-precision and high-resolution measurements of the magnetic field. Together they will provide the necessary observations for the global high-precision survey of the geomagnetic field that is needed to model its various sources.

'Cosmic Vision 2020': the new ESA Science Programme

Following the outcome of the ESA Ministerial Council in Edinburgh in November 2001, the Director of Science undertook a complete reassessment of the ESA Science Programme.

This was done in close collaboration with the science community, represented by the Space Science Advisory Committee, Industry and Member State delegations. The results of this exercise were presented as a proposal to the 99th meeting of the ESA Science Programme Committee in Andenes (Norway) on 22/23 May.

After extensive consultations with all its partners, the Executive could propose a revised plan, which not only maintained the missions approved in October 2000, but added the Eddington mission also. The new plan therefore contains the following missions:

Astrophysics
Group 1: XMM-Newton, Integral;
Group 2: Herschel, Planck, Eddington;
Group 3: GAIA.

Solar System Science:
Group 1: Rosetta, Mars Express, (Venus Express would have been in this group);
Group 2: SMART-1, BepiColombo, Solar Orbiter.

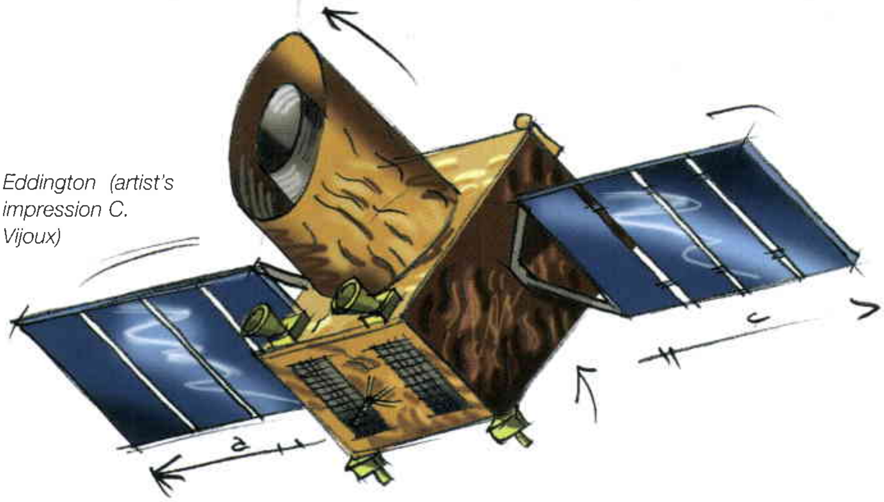
Fundamental Physics:
- STEP (2005) the 'equivalence principle' test,
- SMART2, a technology demonstration mission (2006) for LISA, a joint mission with NASA, searching for gravitational waves (2011).

In addition, the Agency is committed to cooperation with NASA in NGST (the Next Generation Space Telescope), the successor of the Hubble Space telescope, with launch in 2010. STEP (2005), the mission to test of the nature of mass and the basis of mechanics, relies on a decision by NASA, the major partner.

The 'production groups' indicated are more than scientific groupings. Missions within each will be built synergistically using common technologies and engineering teams where possible.

Such a scenario is going to rely on specific commitment to new ways of working, e.g.the implementation of BepiColombo and Solar Orbiter with international partners. Both missions will be implemented as a single activity, leading to significant savings. Other examples are the planned implementation of Herschel/Planck and Eddington in a single project, re-using the same bus, and significant gains through new technology in terms of the cost-effectiveness of spacecraft development and procurement.

Whilst the new name 'Cosmic Vision 2020' refers to the universe, the programme is also providing vision in technological and managerial innovation here on Earth. The overall funding assumption underlying the new plan is that purchasing power will be preserved in the years following 2005. esa



Eddington (artist's impression C. Vijoux)

Mars — an island in Canada?

What is the best method for astronauts to take samples on a future mission to Mars? A good way to find out is to go to a place on Earth that resembles the Martian surface, put on a simulated space suit, and try. One of the most Mars-like places on Earth is the barren Devon Island in the Canadian Arctic, where the Flashline Mars Arctic Research Station (FMARS) provides a unique environment for the simulation of the human exploration of Mars. A crew of six scientists and engineers, all with different mission objectives, took part in the summer expedition to FMARS in July 2002.

Author Markus Landgraf was member of the crew. His objective was to take minimally contaminated samples from the surface for an exobiology experiment by the Geophysical Laboratory of the Carnegie Institute and, at the same time, to test sampling techniques under simulated planetary extra-vehicular activity (EVA) conditions. The other crew members were: Robert Zubrin (commander), Nell Beedle, Frank Eckardt, Shannon Hinsa, and Emily MacDonald. K. Mark Caviezel served as armed escort for the crew during EVAs to protect us from potential polar bear attacks.

One major goal of the human exploration of our Solar System in general and Mars in particular is the search for extraterrestrial life. If you want to prove the existence of past or current Martian life you have to send astronauts to the surface. Well-trained astronauts can decide on the spot whether a sample is interesting for further analysis. What is more, astronauts are more flexible in where they go on the surface and can thus adjust their science agenda to the discoveries they make during the mission.

The FMARS habitat

In order to find out whether the Apollo-approach to taking samples – using generic tools like a hammer, simple drills, and shovels, rather than specialised equipment – is the right one, my colleagues from the Carnegie Institute and I decided to try using simple tools for a sampling campaign during a number of EVAs to at least two different sampling sites close to the Haughton impact crater on Devon Island. The Haughton crater is an impact structure about 16 kilometres in diameter and 23 million years old. Due to its advanced age its rim, where the FMARS habitat is located, as well as its interior are heavily eroded. In the central part one can find breccia, a kind of rock that is created by the shattering force of the impact. Most of the rest of the geology is dominated by dolomite, the magnesium-rich, reddish flavour of limestone. The dolomite layer was created as sediment in the time before the impact when the region that is now northern Canada was the floor of an ocean.


A fresh sample of "Mars rock"

The EVAs took us to two outcrops of indigenous rock close to the habitat. The first, called Devo Rock, is about 12 metres high and the sampling site can only be reached by a decent amount of rock climbing. Climbing the rocks, even in 1 g, turned out to be surprisingly easy in the EVA suits. Of course safety was the top priority, and thus only light tools were used. The old limestone turned out to be quite difficult to crack open. Removing the weathered superficial material and taking samples from two separate sites took about one hour and was pretty strenuous.

During the whole sampling procedure it was obvious that taking samples at this site would have been impossible for a robot. It would be very difficult for a robot even to reach such a site.

On the second EVA our target sampling-site was an outcrop of bedrock called Marine Rock that sits isolated in the Von Braun Planitia, 2.3 kilometres northwest of the habitat. In terms of geology, Marine Rock is very similar to the first site, Devo Rock, but the bedrock there is much easier to reach. Thus, the deep sampling procedure was tested here, which involved more heavy tools like a 10 kg sledgehammer. Applying the sledge-hammer to the edge of the rock turned out to be very demanding. After about 15 minutes of hitting the rock cracks appeared that we widened carefully in order to take samples from a depth of about 10 cm beneath the surface. Taking even deeper samples will require some more specialised tools like a rock drill. In total we took three samples at Marine Rock, wrapped them carefully in aluminium foil and put them in sampling bags, which were finally stored in plastic sampling containers.
In summary the expedition to the FMARS habitat was a valuable experience with quite some lessons learned: Simple generic tools like a geological hammer and wedge are very efficient and can be applied in a wide variety of situations. If the sampling is carried out carefully, the only contamination can come from the tools and the packing material, because it is not necessary to touch the samples with the possibly contaminated glove. The mobility in the EVA suits is surprisingly good, provided one moves with some pre-planning, especially when climbing. Here is the rule of thumb: move slowly and think ahead!

It was amazing how much we learned during our three-week mission to FMARS. As the summer is now over in the Arctic, the Mars Desert Research Station in Utah takes over, where more experiments are to be conducted. Another simulation habitat will be set up by the European chapters of the Mars Society in the volcanic regions of northeastern Iceland. Aptly named EuroMARS this new habitat will allow European scientists and engineers to test operational procedures for planetary exploration in more detail. So step by step we are getting ready for the red planet!

http://www.marssociety.org/arctic/index.asp
http://www.euromars.org

Sample from the Marine Rock site under examination in the laboratory.

Satellite images for humanitarian aid

ESA will assist the Reuters Foundation and its AlertNet service by providing information and imagery from ESA Earth observation missions and promoting the use of satellite remote-sensing data by the international humanitarian aid community. More specifically, ESA will provide access to information from its satellite data archives and from the current ERS-2 and Envisat missions. ESA's Director of Earth Observation Programmes, José Achache, and Reuters Foundation Director, Maureen Marlowe, signed a collaboration arrangement between the Agency and the Foundation in June.

ESA will also involve the Reuters Foundation in the user consultation processes it is conducting for the purpose of identifying the satellite data requirements of humanitarian aid organisations, as a contribution to the definition of the European GMES (Global Monitoring for Environment and Security) programme.

A dedicated "satellite image" web page will be developed on the Reuters Foundation's AlertNet site, with images provided by ESA, setting out a number of case studies and a guide to Earth observation.

ERS-2 image of the flooded areas of the Elbe river around Dresden, Germany, taken on 13 August 2002

Reuters Foundation Director Maureen Marlowe said: *"AlertNet's service to its member organisations will be significantly improved. The pictures and graphics from space will not only show terrain clearly, but enable our member agencies to track the movements of displaced people and monitor the impact of natural disasters such as floods and earthquakes more accurately and quickly"*

The Reuters Foundation, created in 1982, is a humanitarian and educational trust, primarily funded by Reuters, the global news, information and technology group. The AlertNet service was launched in 1997 to provide fast news and communications for international disaster relief. Membership of the service currently includes more than 175 aid agencies from 35 countries. AlertNet acts as a platform for vital communication and information sharing within the humanitarian aid community worldwide.

New round for SME funding

ESA has launched a second and expanded round of funding for innovative R&D initiatives in satellite communications from Small and Medium-sized Enterprises (SMEs).

ESA's first round of funding last year is already supporting projects in such fields as transportation management, tracking systems, integration of satellite IP networks and interactive satellite advertising.

Claudio Mastracci, ESA's Director of Applications, commented: "*Building on our experience with the first initiative, we have fine-tuned the scheme to increase flexibility and the support we provide throughout the application process.*"

Companies selected to join the scheme will be offered technical and financial support of up to 300 000 Euros to develop their concepts to a level where commercial funding can be sought. The scheme might fund new uses for existing satellite technologies (to provide new Internet, multimedia, location-based communication or mobile applications) or support new systems and technologies with the potential to improve existing services.Two possible funding levels are available, depending on the commercial maturity of the proposal.

ESA and NIVR sign agreement for User Support and Operations Centre at ESTEC

B. Droste (left) and J. Feustel-Büechl shake hands on the new agreement

At the end of February, J. Feustel-Büechl, ESA Director of Manned Spaceflight and Microgravity, and B. Droste, Chairman of the Board of NIVR (Netherlands Agency for Aerospace Programmes) signed an agreement on a special financial contribution by the Netherlands Ministry of Economic Affairs to the creation of the Erasmus User Support and Operation Centre (USOC).

The Erasmus USOC will be installed in the Erasmus Building at ESA's European Space Research and Technology Centre (ESTEC) and will add to the existing International Space Station User Information Centre and the European Robotic Arm Support Centre.

The Erasmus USOC will be responsible for the preparation and execution of the operation of the European Drawer Rack (EDR), which is a flexible multi-user facility located inside the Columbus Laboratory, and of the European Technology Exposure Facility located on the Columbus external platform. The agreement permits the procurement of operations test equipment and software dedicated to the EDR. It complements the participation of Belgian industry previously agreed with the Belgian Delegation, which focuses on the first EDR payload: the Protein Crystallisation Diagnostics Facility (PCDF).

esa

Visiting and Returning from Space Safely

How best to achieve the goal of 'Flying to and Returning Safely from Space!' was the main focus of the first Joint ESA-NASA Space Flight Safety Conference held at ESA's ESTEC establishment in Noordwijk (NL) from 11 to 13 June. This three-day Conference emanated from an idea to jointly organise and expand the scope of the existing NASA Payload Safety Conference to include more general system-safety aspects.

A new era in manned space flight is gradually emerging in which effective partnership, information exchange and mutual responsibility are the overriding factors. The aim of the Noordwijk Conference was to provide a forum for the exchange of ideas and to forge closer links between space agencies as well as international industry. Hence the choice of 'Safety Through Partnership' was chosen as the Conference slogan.

This Conference was an important step for ESA in its role as a Partner in the International Space Station (ISS) Programme, which includes more responsibility and greater autonomy in the field of safety than any previous collaborative programme with NASA. This calls for enhanced cooperation between ESA and NASA specialists in all fields related to payload flight safety.

The two main Conference topics, addressed in 14 complementary sessions, were:
- System Safety and Risk Management
- Payload Safety and Certification

both of which were extensively discussed in the context of the design, development, verification, validation and operation of space systems. Over 150 international delegates attended, including representatives from the Japanese Space Agency (NASDA), the Rocket Space Corporation, Energia, Rosaviakosmos and the Indian Space Research Organisation (ISRO).

The Conference provided a lively forum for presentations and discussions on the two main topics, as well as poster presentations and the demonstration of innovative software and training material. The plenary closing session provided an opportunity for conclusions and recommendations to be formulated and discussed.

The Risk Management sessions resulted in the conclusion that there is a need for greater international collaboration regarding the implementation of risk-management techniques and practices. The implementation should involve the definition of risk-management policy, procedures and training with a long-term view towards normalising such procedures and techniques across the international aerospace community. Information regarding successes and failures should also be more widely shared in an attempt to achieve a positive risk-management culture across the aerospace sector.

The Payload Safety sessions were mainly dedicated to the presentation of currently applied safety requirements and lessons learnt, together with proven means of compliance. Commercial activities involving safety usually require licensing and enforced adherence to government-imposed regulations. In this context, it was suggested that the ISS might well evolve over time into a hybrid government/private system, and therefore existing safety rules and processes (created primarily for multi-national government operations) would have to be standardised to properly address this metamorphosis.

It was also recommended that ISS commercialisation, and indeed the international structure of the ISS Programme itself, would benefit greatly from the establishment of a single independent safety authority. It was envisaged that each ISS Partner would participate in this single authority, exercising the roles and responsibilities assigned to them via inter-governmental agreements and memoranda of understanding.

The full Proceedings of the Conference are already available from ESA Publications Division as ESA SP-486 (Price 50 Euros: Order Form inside the back cover of this Bulletin).

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PREPARING FOR THE FUTURE, VOL. 12, NO. 2 (JULY 2002)
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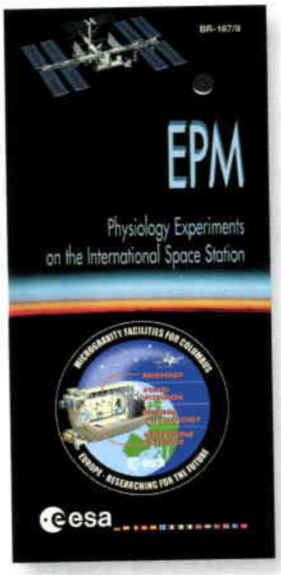

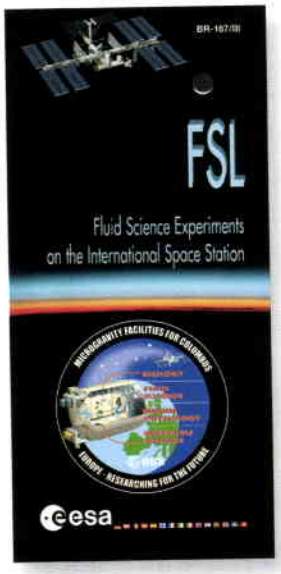

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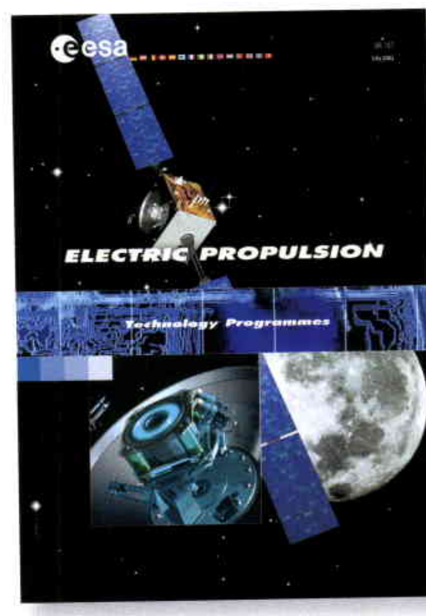

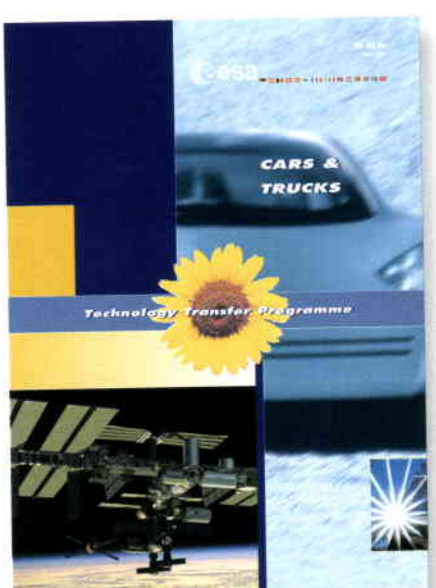

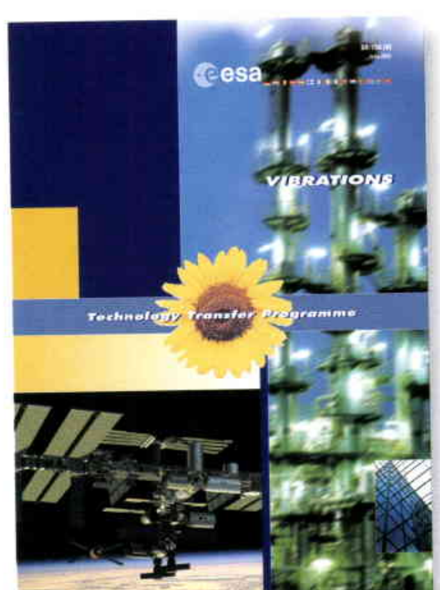

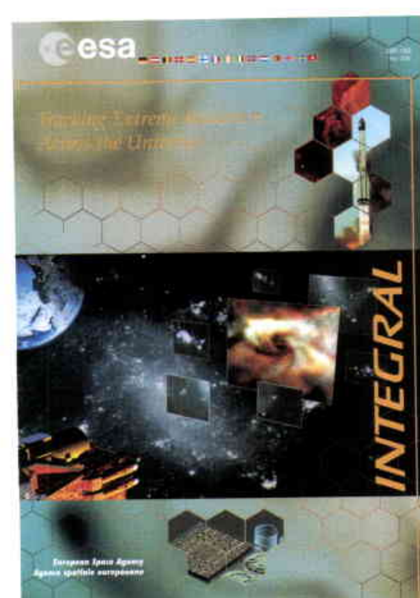

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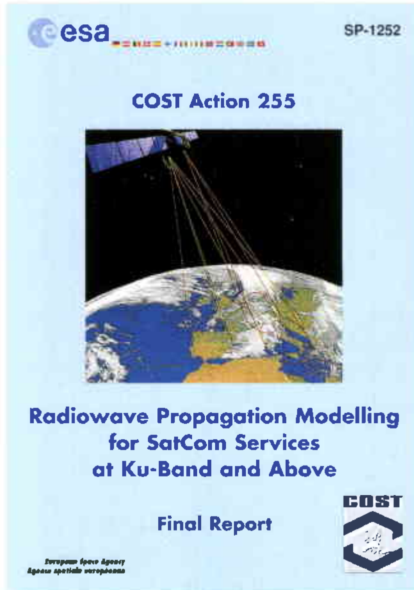

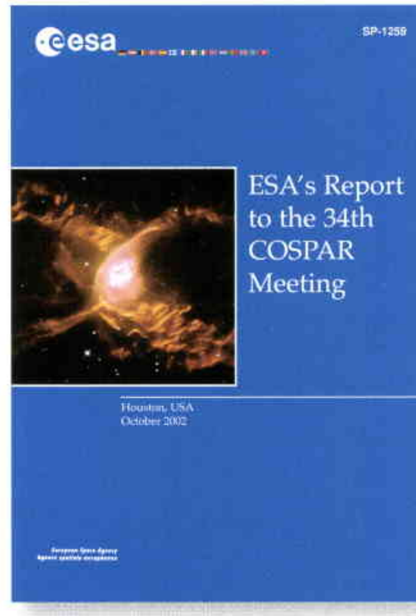

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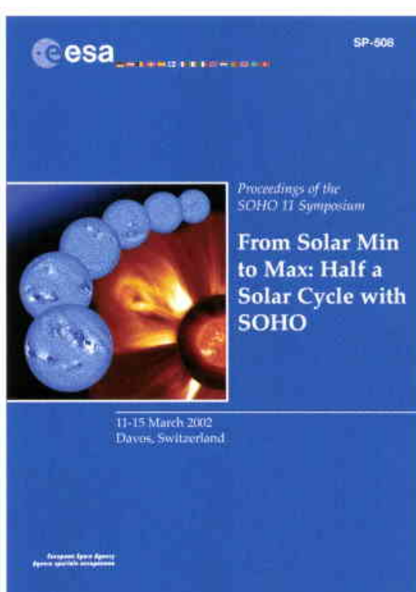

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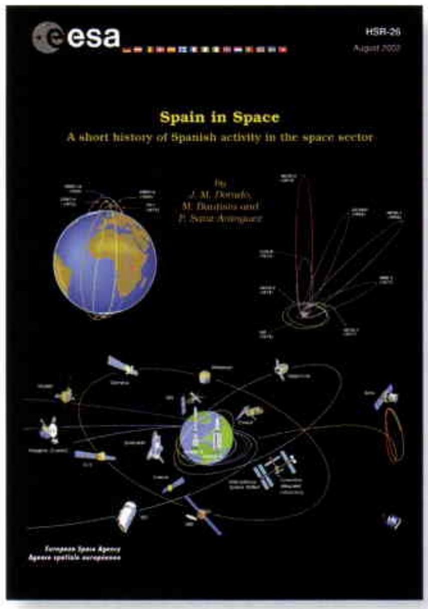

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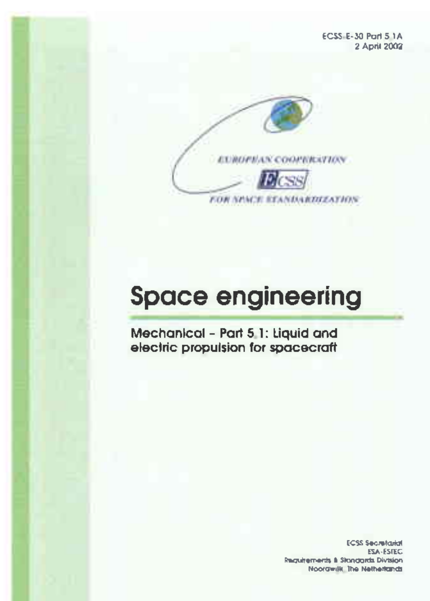

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