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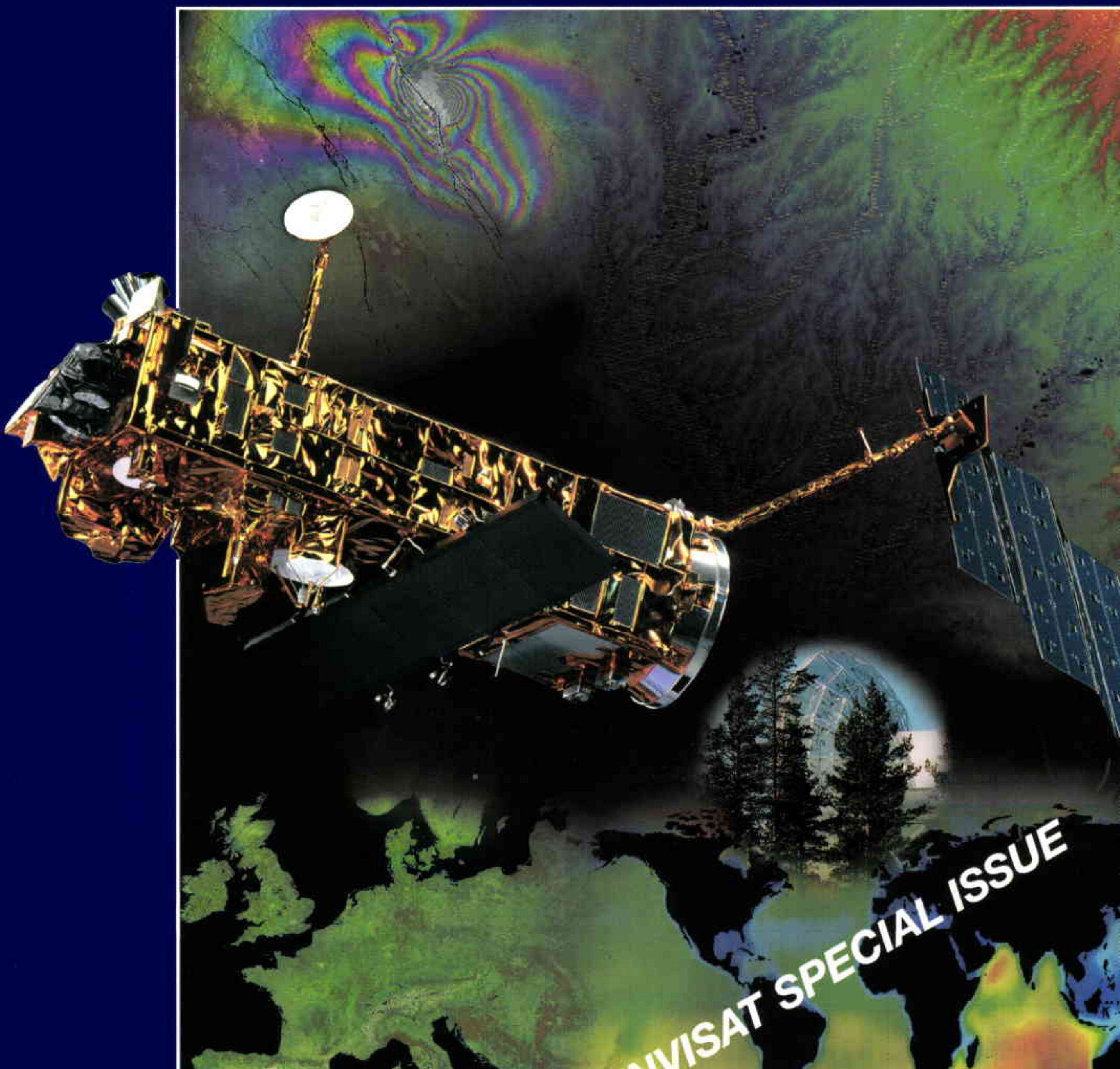

European Space Agency
Agence spatiale européenne

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, Portugal, 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.

The ESA HEADQUARTERS are in Paris.

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THE EUROPEAN SPACE OPERATIONS CENTRE (ESOC), Darmstadt, Germany

ESRIN, Frascati, Italy.

Chairman of the Council: A. Bensoussan

Director General: A. Rodotà

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.

Selon les termes de la Convention: l'Agence a pour mission d'assurer et de développer, à des fins exclusivement pacifiques, la coopération entre Etats européens dans les domaines de la recherche et de la technologie spatiales et de leurs applications spatiales, en vue de leur utilisation à des fins scientifiques et pour des systèmes spatiaux opérationnels d'applications:

(a) en élaborant et en mettant en oeuvre une politique spatiale européenne à long terme, en recommandant aux Etats membres des objectifs en matière spatiale et en concertant les politiques des Etats membres à l'égard d'autres organisations et institutions nationales et internationales;
(b) en élaborant et en mettant en oeuvre des activités et des programmes dans le domaine spatial;
(c) en coordonnant le programme spatial européen et les programmes nationaux, et en intégrant ces derniers progressivement et aussi complètement que possible dans le programme spatial européen, notamment en ce qui concerne le développement de satellites d'applications;
(d) en élaborant et en mettant en oeuvre la politique industrielle appropriée à son programme et en recommandant aux Etats membres une politique industrielle cohérente.

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ESRIN, Frascati, Italy

Président du Conseil: A. Bensoussan

Directeur général: A. Rodotà

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ENVISAT SPECIAL ISSUE


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EOQ N° 69 - June 2001
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QUARTERLY
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Welcome to the new look Earth Observation Quarterly – we hope you like it!
The EOQ Steering Committee wants this newsletter to be the vehicle for news about all of the Agency's varied activities in the area of Earth Observation and Environment Monitoring from Space and to reach a wider readership.
We plan to carry more short news items about projects and other EO-related activities, while still retaining the more specialised articles, which will in general be a little shorter. Eventually we would like to introduce a few tutorial items and invite you to suggest topics (and to propose articles).
The centre spread of each issue will typically showcase one or two attractive image products generated by the EO Applications Department in ESRIN.
Please let us know what you think of the new style. Constructive feedback will help us to deliver the newsletter best suited to your needs.
The Editors and the Steering Committee

Foreword

As we enter this new millennium, proper management of the Earth's resources and protection of the Earth's environment are two major and pressing concerns for the future of humanity. In this new battle, Earth observation from space is making a major contribution. In less than two decades, it has become a primary tool with which to observe the globe, providing the scientists with the data needed to validate and maintain global models, as well as to observe the tiniest movements and changes on Earth, which is essential to monitor landslides, earthquakes, volcanoes, glacier melting, etc.

In this context, the decision by ESA's Member States in the early 1990s to embark on the Envisat Programme, as a successor to the highly successful ERS-1 and -2 missions, clearly demonstrated Europe's determination to play a leading role in Earth environment monitoring. The Envisat satellite - carrying ten instruments to provide synergetic observations over the oceans, land, ice caps and atmosphere - is the biggest civilian Earth Observation satellite ever built. Its development programme - a major challenge for ESA and European space industry - has been successfully concluded within the approved financial envelope. The satellite itself is already in Kourou (Fr. Guiana) ready for its Ariane-5 launch in the autumn.

The Envisat Programme also includes the means for providing a suite of calibrated and validated products to the users, with stringent delivery requirements. For these services, a large Payload Data Segment has been developed, complemented by national facilities and use of ESA's Artemis data-relay satellite. With 700 projects already selected from the first Announcement of Opportunity (AO) for data exploitation, several thousand scientists, from all over the world, are eagerly awaiting the first data from Envisat to begin their pilot application projects. In parallel, two selected product distributing consortia, already at work with ERS data, are ready to promote the commercial distribution of Envisat products and services.

Before starting this wide product distribution, the instruments themselves have to be calibrated and the products validated. This is the challenge faced during the first six months of in-orbit commissioning, which will involve hectic working by and close cooperation between engineers and scientists, with a large number of in-situ measurements, correlations with models, and a major data-analysis effort.

Envisat, together with the forerunner ERS missions, will provide an unprecedented, continuous and coherent set of global and regional observations spanning almost two decades. Responding very well indeed to the needs expressed by the recent European Commission initiative for Global Monitoring for Environment and Security (GMES), Envisat will be an excellent mission with which to explore and develop the various services envisaged.

Beyond Envisat, the ESA Earth Observation Strategy is already well-established. The Envelope Programme that is already in place is ensuring the pioneering of new observation techniques with Explorer and Opportunity Missions, while the Earth Watch Programme, currently under discussion with ESA's Member States, will ensure the eventual implementation of operational services, in partnership with operational/commercial entities. Both Programmes are on the agenda for discussion at the ESA Council at Ministerial Level in Edinburgh in November this year.

With Envisat's launch, Europe is endorsing both its leading role in Earth observation from space and its commitment to preserving the vulnerable environment of our living planet.

C. Mastracci
Director, ESA Application Programmes


Envisat

The Envisat Mission and System

J. Louet
Envisat Programme Manager, ESA Directorate of Earth and Environment Monitoring from Space, ESTEC, Noordwijk, The Netherlands

While our planet, throughout its long history, has undergone a natural evolution in its physical characteristics, it is now recognised that our growing human activities can directly affect our environment. An increasing population and expanding development demands are placing heavy stresses upon the finite resources of the Earth's system. There is also an increased awareness of the human and economic impact of the variability of our environment, particularly when facing natural disasters such as floods, earthquakes or volcanic eruptions. This growing concern has resulted in international agreements aimed at monitoring and minimising manmade environmental damage.

For the monitoring of environmental changes, the major contribution from satellites through their systematic observation of the Earth is now fully acknowledged. They offer both global observations for worldwide environmental needs and regional observations to support local environmental monitoring. Continuity of these observations is of paramount importance to identify and separate seasonal variations from long-term trends. The main objective of the Envisat programme is therefore to endow Europe with an enhanced capability for the remote sensing of the Earth from space. It significantly increases Europe's capacity to take part in the study and monitoring of the Earth and its environment, following the very successful ERS-1 and ERS-2 missions.

Introduction

The Envisat satellite is composed of the payload complement and the Polar Platform (PPF) on which the instruments are mounted. It carries a package of ten multi-disciplinary instruments to observe the Earth and its atmosphere from space in a synergistic fashion, offering unprecedented opportunities in environmental monitoring and operational Earth observation. It addresses crucial matters such as global warming, climate change, ozone depletion and ocean and ice monitoring. As such, it will be a major contributor to the global study and monitoring of the Earth and its environment, as expressed by international cooperative endeavours such as the International Geosphere–Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP).

The Envisat mission is designed to provide synergistic measurements over:

– oceans
– land
– ice caps
– atmosphere

thereby offering capabilities for global monitoring as well as precise local/regional observations, supporting in particular pollution and disaster monitoring. In this respect, Envisat responds very well to the recent European Commission initiative for the Global Monitoring of our Environment and Security (GMES) and will provide the basic data products needed for developing the required applications and services.

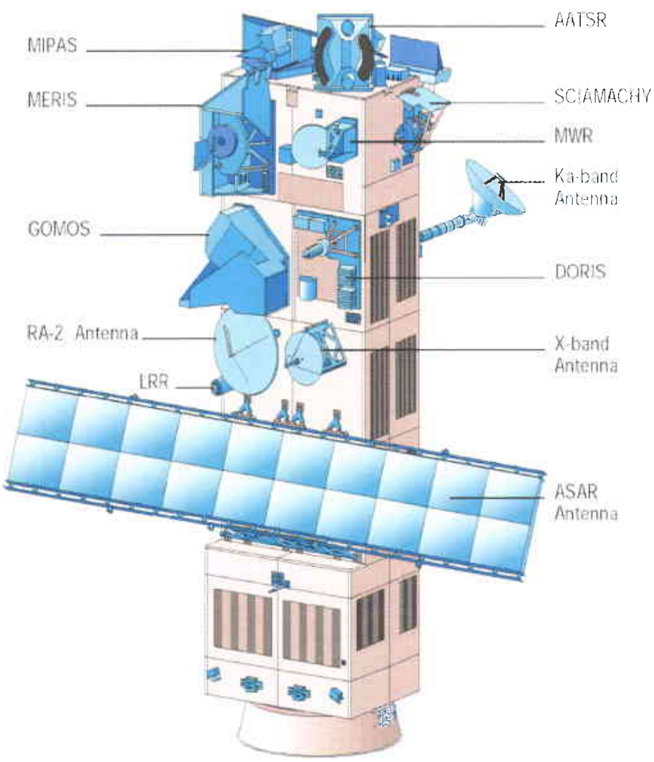
With the successful completion of the Envisat development programme and the satellite's imminent launch by an Ariane-5 from Kourou (Fr. Guiana) this autumn, the European space community is demonstrating its ability to develop advanced Earth-observation instruments meeting challenging performance requirements, and thereby confirming its leading role in Earth observation.

The satellite and its payload

The Envisat satellite is composed of the payload complement and the Polar Platform (PPF) on which the instruments are mounted (Fig. 1). Its orbit will be Sun-synchronous, with the same repeat cycle as that of ERS-2. The two orbits will be phased to have the same ground track, with Envisat preceding ERS-2 by half an hour.

The payload

The payload comprises a set of ESA-Developed Instruments (EDIs) complemented by Announcement-of-Opportunity Instruments (AOIs) developed on a national basis.



Dimensions
- Launch configuration: length 10.5 m, envelope diameter 4.57 m
- In-Orbit Configuration: 26 m x 10 m x 5 m

Mass: Total satellite 8140 kg
(Payload 2050 kg)

Solar array power: 6.5 kW (EOL)

Average power demand:

	Sun (watts)	Eclipse (watts)
Payload	1700	1750
Satellite	3275	2870

Launch vehicle: Ariane-5 (single launch)

Orbit: Sun-synchronous, 800 km mean altitude
35-day repeat cycle
10:00 descending node mean local solar time

Figure 1. The main characteristics of the Envisat satellite

The EDIs are:
- MERIS (Medium-Resolution Imaging Spectrometer)
- MIPAS (Michelson Interferometric Passive Atmospheric Sounder)
- ASAR (Advanced Synthetic-Aperture Radar)
- GOMOS (Global Ozone Monitoring by Occultation of Stars)
- RA-2 (Radar Altimeter 2)
- MWR (Microwave Radiometer), and
- LRR (Laser Retro-Reflector).

Disciplines / Instruments	ASAR	GOMOS	RA-2	MERIS	MIPAS	MWR	LR	SCIAMACHY	DORIS	AATSR
Atmosphere										
Clouds				■				■		■
Humidity						■				
Radiative Fluxes				■						■
Temperature					■			■		
Trace Gases		■			■			■		
Aerosols		■		■	■			■		■
Land										
Surface Temperature										■
Vegetation Characteristics	■			■						■
Surface Elevation	■		■				■		■	
Ocean										
Ocean Colour				■						
Sea Surface Temperature										■
Surface Topography			■				■			
Turbidity				■						
Wave Characteristics	■		■							
Marine Geoid			■							
Ice										
Extent	■			■						■
Snow Cover	■			■						■
Topography	■		■				■			
Temperature										■

Figure 2. The contributions of the different Envisat instruments to the meeting of mission objectives

The AOIs are:
- SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography)
- AATSR (Advanced Along-Track Scanning Radiometer), and
- DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite).

Part of the instrument complement is focussed on ensuring continuity of the data acquired by the ERS instruments – ASAR, AATSR and RA-2 with its supporting instrumentation (MWR, DORIS and LRR) – with improved accuracy and coverage. Observation of the oceans and coastal waters (with the retrieval of marine-biology constituent information) is the primary objective of the MERIS instrument. ASAR brings a new dimension to the applications and services already pioneered with the ERS Synthetic-Aperture Radar (SAR), by offering different incidence angles at high resolution, dual polarisation, wide-swath medium resolution, as well as an enhanced wave mode. The ability to observe the atmosphere, following on from the GOME instrument on ERS-2, is significantly enhanced by three instruments on Envisat that offer complementary measurement capabilities in terms of limb and nadir observations for a large variety of trace-gas concentrations and profiles through their specific absorption features.

The synergy of these ten instruments as a function of mission objectives is illustrated in Figure 2, demonstrating the comprehensive capabilities of Envisat for observing our planet's land masses, oceans, ice caps and atmosphere.

The satellite

The Envisat satellite is composed of two major elements: the Polar Platform and the instrument suite constituting the Earth-observation payload. A major driver for the overall satellite configuration has been the need to maximise the mounting area for the payload instruments and to meet their viewing requirements, whilst staying within the constraints of the Ariane-5 fairing and interfaces. The Polar Platform is a large modular construction comprising two major assemblies, the Service Module and the Payload Module (Fig. 3).

The *Service Module (SM)* provides the basic satellite functions of power generation, storage and distribution, attitude and orbit control, S-band telemetry and telecommand communication, and data handling for the overall satellite-control functions. The SM is based on the concept and design of the Spot-4 service module, but with a number of important new developments, particularly in the mechanical design area.

The *Payload Module (PLM)* consists of the Payload Carrier (PLC) and the Payload Equipment Bay (PEB). The PLC provides mounting surfaces of 6.4 m x 2.75 m for the payload instruments and associated electronics. The payload-dedicated support systems are mounted in the PEB. The payload support functions include instrument control and data handling, X-band and Ka-band communications, power distribution, mechanical support and thermal control.

The payload capabilities versus mission objectives

The payload complement addresses four major areas:

- radar imaging, with ASAR
- optical imaging over oceans, coastal zones and land, with MERIS and AATSR
- observation of the atmosphere, with GOMOS, MIPAS and SCIAMACHY
- altimetry, with RA-2, supported by MWR, LRR and DORIS.

Radar imaging

The Advanced Synthetic-Aperture Radar (ASAR)

The ASAR is a high-resolution, wide-swath imaging radar instrument. Its main objective is to monitor the Earth's environment and to collect information on:

- ocean-wave characteristics
- sea-ice extent and motion
- snow and ice extent
- surface topography
- land-surface properties
- surface soil moisture and wetland extent
- deforestation, and extent of desert areas
- disaster monitoring (floods, earthquakes, etc).

The major advantage of using a SAR instrument for these Earth-observation tasks is its ability to take images independent of weather conditions, cloud coverage and solar illumination. Considering in particular observations of disasters like floods, which usually happen during persistent adverse weather conditions, this weather independence is of vital importance.

Compared to the Active Microwave Instrument (AMI) on ERS-1 and ERS-2, the ASAR is a significantly more advanced instrument

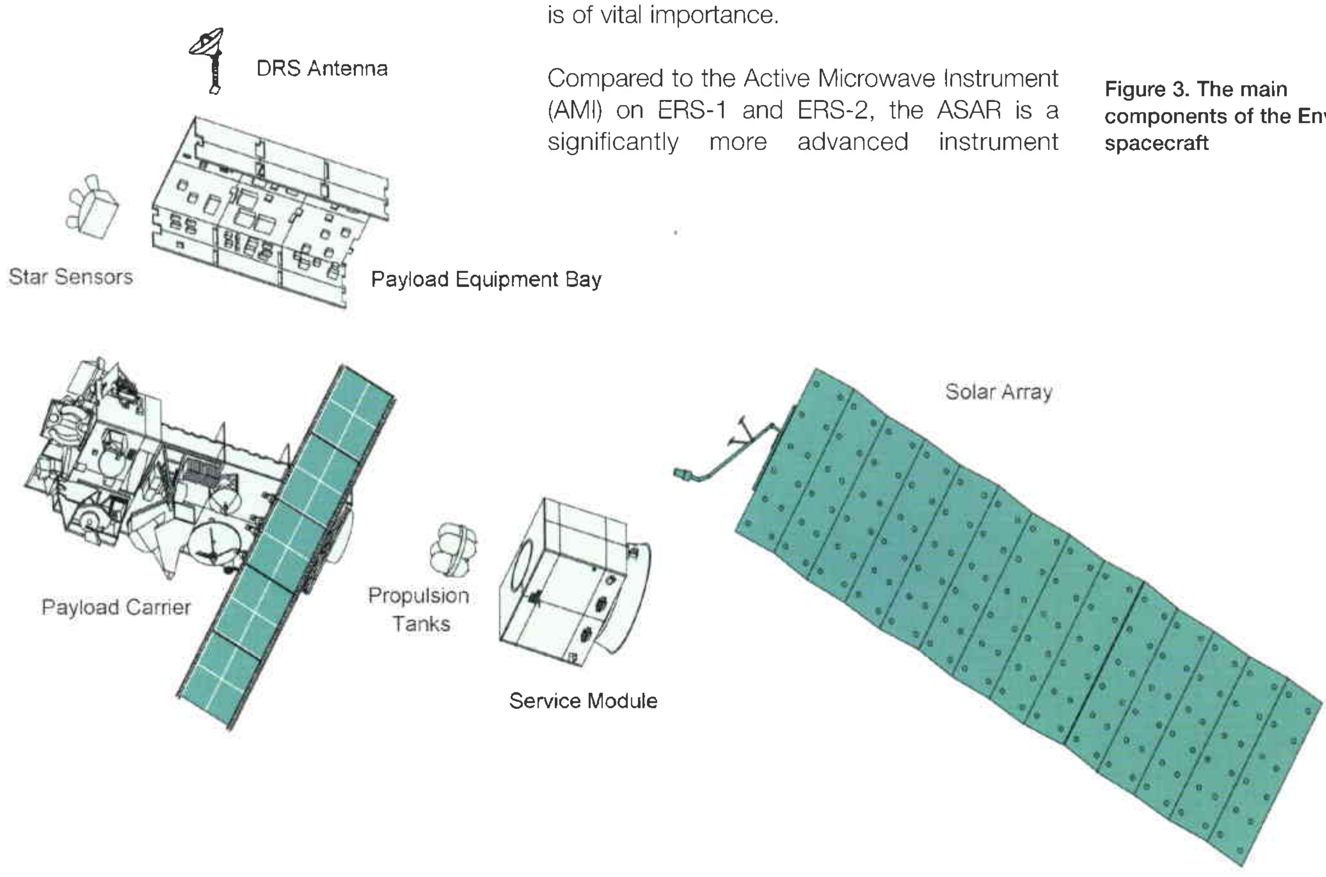


Figure 3. The main components of the Envisat spacecraft

employing a number of new technological developments, where the replacement of the passive radiator array of the AMI by an active phased-array antenna system using distributed elements was the most challenging one. The resulting improvements include the ability to provide more than 400 km wide swath coverage using ScanSAR techniques, and the alternating-polarisation feature allowing scenes to be imaged simultaneously in vertical (V) and horizontal (H) polarisation.

The ASAR instrument is designed to operate in the following principal modes:
- image
- wide swath
- wave
- alternating polarisation
- global monitoring.

The observing geometries of these different modes are illustrated in Figure 4.

In image mode, the ASAR gathers data from relatively narrow swaths (100 km within a viewing area of approx. 485 km) with high spatial resolution (30 m), whereas in wide-swath mode using ScanSAR techniques a much wider stripe (400 km) is imaged with lower spatial resolution (150 m).

In wave mode, the ASAR measures the change in radar backscatter from the ocean due to surface waves. Wave spectra are extracted fom 5 km x 5 km imagettes taken over the ocean at 100 km intervals. The alternating-polarisation mode provides imaging of a scene with alternating polarisation during transmission and reception. The spatial resolution is equal to that of the image mode. In global-monitoring mode, a wide swath (400 km) is imaged with 1000 m spatial resolution.

The low data rates in wave and global-monitoring mode are recorded all around the satellite's orbit, while the high-data-rate modes are operated upon user request. The radar images obtained by ground processing of the ASAR data will allow the generation of enhanced products suited to applications over land surfaces, ocean and coastal regions, and ice zones.

Optical imaging over oceans, coastal zones and land

These observation capabilities are offered by two complementary instruments: MERIS and AATSR.

The Medium-Resolution Imaging Spectrometer (MERIS)

MERIS addresses the needs of three disciplines, primarily oceanographic but also atmospheric and land observations. Complemented by the RA-2 and AATSR instruments, it provides a unique synergistic mission for

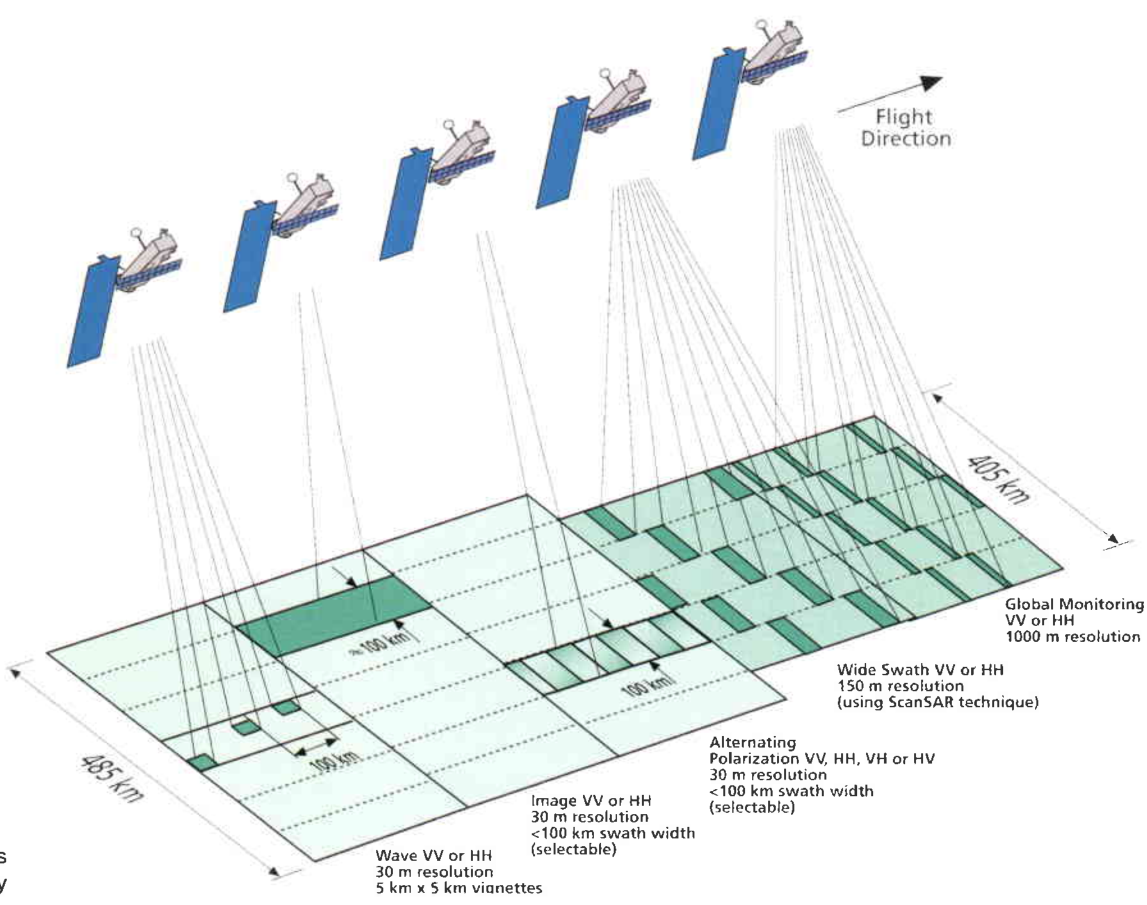


Figure 4. The ASAR modes and observation geometry

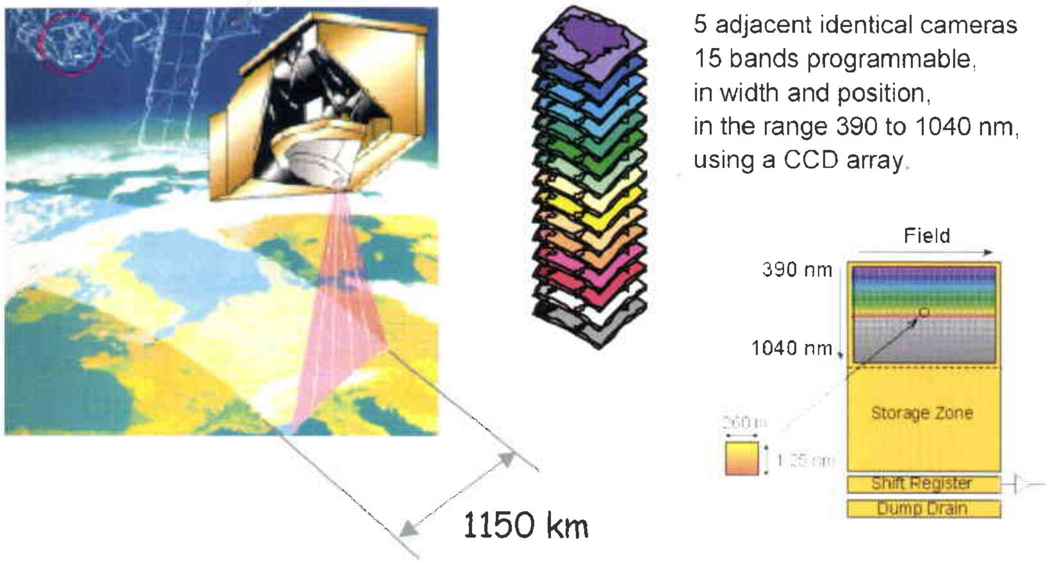


Figure 5. The operating principle of MERIS

bio/geophysical characterisation of the oceans and coastal zones, and thus for global climatological and environmental studies and monitoring.

MERIS is a push-broom instrument measuring the solar radiation reflected from the Earth's surface and from clouds in the visible and near-infrared range (390 – 1040 nm). The 1150 km-wide swath is provided by five identical adjacent cameras (Fig. 5). Each camera images an across-track stripe of the Earth's surface onto the entrance slit of an imaging optical-grating spectrometer. This entrance slit is imaged through the spectrometer onto a two-dimensional CCD array, thereby providing spatial and spectral information simultaneously.

MERIS features a high degree of flexibility. Fully programmable on-board processing allows the selection of up to 15 different spectral bands in the 1.25 – 30 nm range. The spatial information along-track is determined by the push-broom principle via successive read-outs of the CCD-array. Full-spatial-resolution observations, i.e. 250 m at nadir, will be made over coastal zones and land surfaces. Reduced-spatial-resolution data, achieved by the on-board combination of 4 x 4 adjacent pixels across-track and along-track, resulting in a resolution of approximately 1000 m at nadir, will be generated and recorded onboard over the full Sun-illuminated segment. The instrument is optimised for absolute and relative radiometric performances, featuring regular updating of calibration parameters applied on-board via dedicated calibration hardware to achieve long-term stability.

The instrument data will be processed on the ground to provide spectral images of the Earth corrected for atmospheric influences. These data will be used for the generation of large-scale maps for, for example:

- ocean pigment concentrations
- ocen phytoplankton biomass production (a major factor in the carbon cycle)
- coastal-water monitoring
- clouds and water vapour, and
- vegetation status and distribution.

The Advanced Along-Track Scanning Radiometer (AATSR)

The prime objective of the AATSR is to establish continuity of the ERS ATSR-1 and -2 data sets of precise Sea-Surface Temperature (SST), thereby ensuring the production of a unique 15 year near-continuous data set at the levels of accuracy required (0.3 K or better) for climate research and for the operational and scientific user communities already established with the ERS-1 and -2 missions.

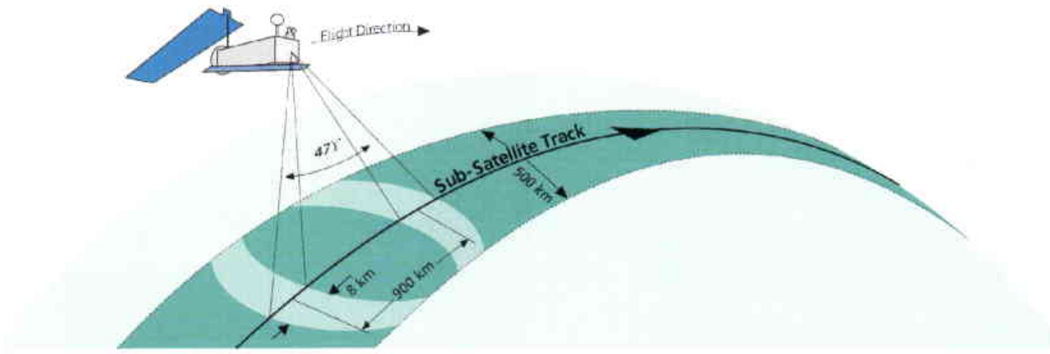
The second objective is to obtain precise land-vegetation measurements, through observations in three visible channels, exploiting the improved visible-wavelength atmospheric correction that will be achievable with the AATSR's two-angle view, thus providing estimates of:

- vegetation biomass
- vegetation moisture
- vegetation health and growth stage.

The above parameters will be used to derive Global Vegetation Indices. The visible channels will also be used to measure cloud parameters like water/ice discrimination and particle size distribution.

The AATSR field of view comprises two 500 km-wide curved swaths, with pixel sizes of 1 km x 1 km at the centre of the nadir swath and 1.5 km x 2 km at the centre of the forward swath. The two views result from the instrument's conical scanning mechanism (Fig. 6). As the two views of the same scene are taken through different atmospheric path

Figure 6. The AATSR viewing geometry

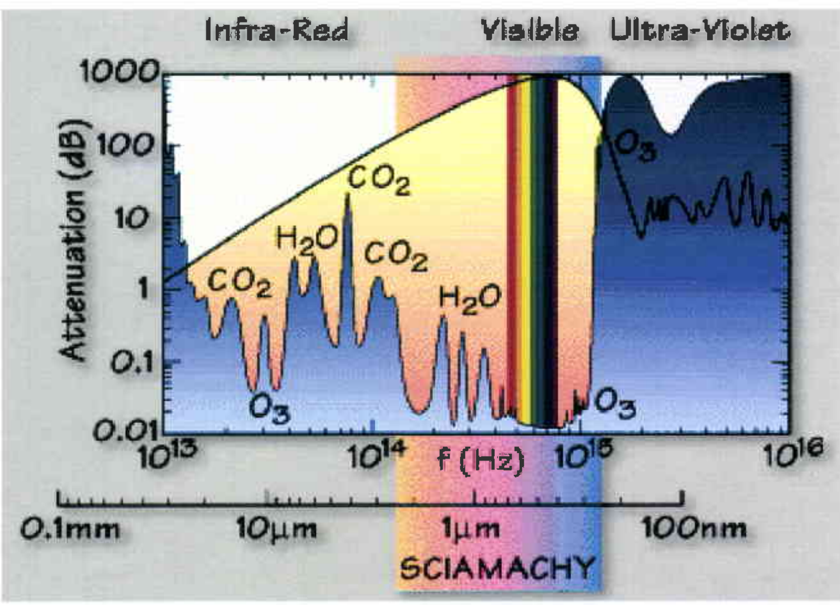


lengths, it is possible to calculate a correction for the effect of atmospheric absorption.

This principle of removing atmospheric effects in SST measurements by viewing the sea surface from two angles is the basis of the (A)ATSR family of instruments. The SST objectives will be met through the use of thermal-infrared channels (centred on 1.6, 3.7, 10.7 and 12 μm), identical to those on ATSR-1 and -2.

The visible channels will provide accurate quantitative measurements of radiation from the Earth's surface, using an on-board calibration system for basic radiometric accuracy, and a two-angle viewing technique to obtain accurate atmospheric corrections. The two most important visible channels, at 0.67 and 0.87 μm, provide measurements of Vegetation Index, and the additional channel at 0.55 μm supports the determination of the state of vegetation (chlorophyll content).

Figure 8. Trace-gas absorption lines



Observation of the atmosphere

Three instruments are dedicated to observation of the atmosphere: GOMOS, MIPAS and SCIAMACHY. Their complementarity for observing primary trace gases is illustrated in Figure 7. Whilst using different observation techniques, all three instruments rely upon analysis of the specific absorption lines created by the gases in the observed spectra (Fig. 8)

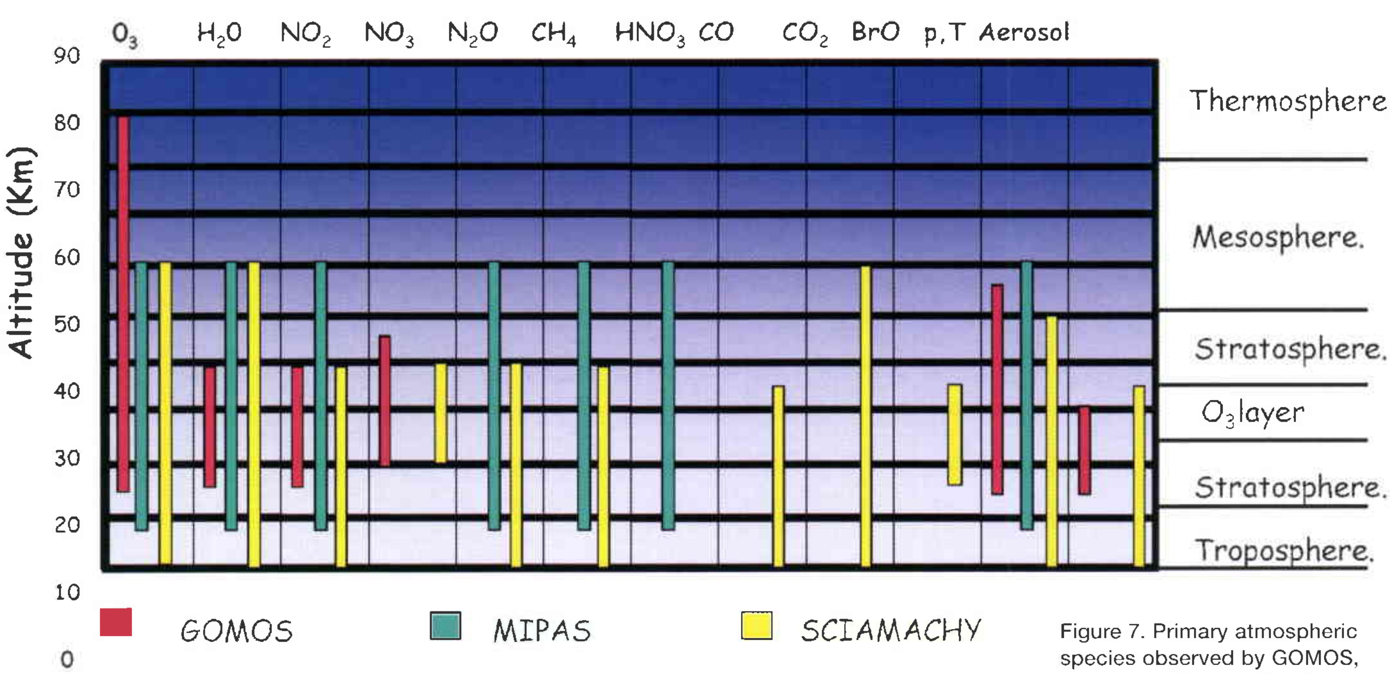


Figure 7. Primary atmospheric species observed by GOMOS, MIPAS and SCIAMACHY

Global Ozone Monitoring by Occultation of Stars (GOMOS)

The GOMOS instrument has been designed to enable simultaneous monitoring of ozone and other trace gases, as well as aerosol and temperature distributions in the stratosphere. It also supports the analysis of atmospheric turbulences. Trace-gas concentrations and other atmospheric parameters will be measured at altitudes between 20 and 100 km with a vertical resolution of approximately 1.7 km.

The instrument accommodates a UV-visible and a near-infrared spectrometer fed by a telescope which has its line of sight orientated towards the target star by means of a steerable mirror. The instrument then tracks the star and observes its setting behind the atmosphere (Fig. 9).

GOMOS will be operated continuously over the full Envisat orbit. About 25 stars brighter than $M_V = 2$ can be observed routinely at different longitudes from each orbit. The GOMOS instrument will produce as much data as a global network of 360 ground stations. The instrument will typically be commanded to observe a sequence of up to 50 stars repeatedly during sequential orbits.

The excellent performance of the GOMOS instrument stems from:

- the self-calibrating measuring scheme by detecting a star's spectrum from outside and through the atmosphere
- the drift- and background-compensating measurement algorithms introduced by the use of two-dimensional array detectors, which allow stellar and background spectra to be recorded simultaneously.

As a result, the spectra are easily corrected for background or stray-light and detector dark-current contributions. Thus, high stability is obtained from simple relative measurements. Over a five-year mission period, ozone-level changes as low as 0.05% per year can be detected, which is far below the depletion rate expected from model calculations.

Michelson Interferometer for Passive Atmospheric Sounding (MIPAS)

MIPAS is a high-resolution Fourier Transform infrared spectrometer designed to measure concentration profiles of various atmospheric constituents on a global scale. It will observe atmospheric emissions from the Earth's horizon (limb) in the mid-infrared region (4.15–14.6 micron), providing global observations of photo-chemically interrelated trace gases in the middle atmosphere and upper troposphere.

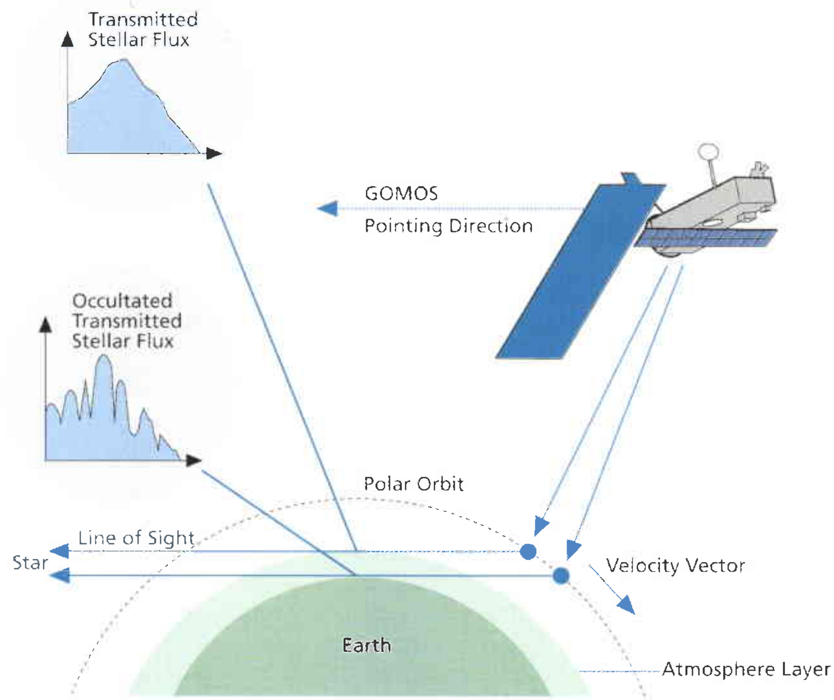


Figure 9. GOMOS observing principle

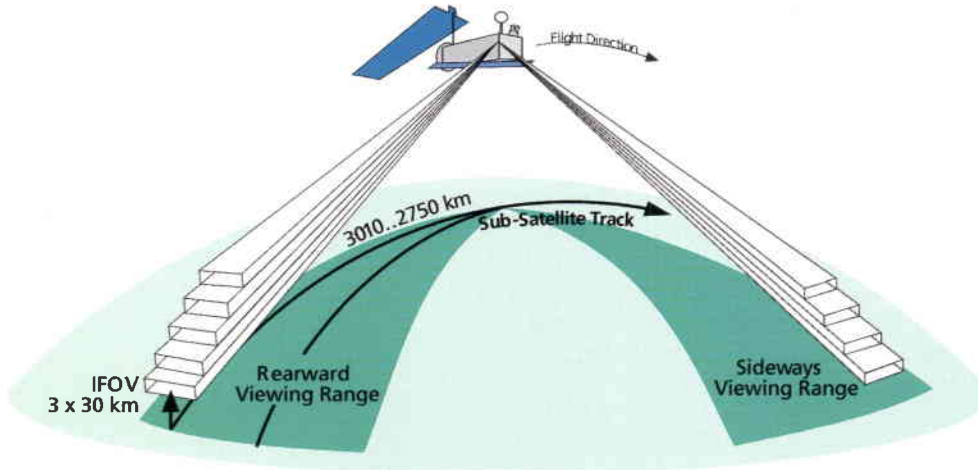
These data will contribute to the development of a better understanding in the following research areas:

- Stratospheric Chemistry: global ozone problem, polar stratospheric chemistry.
- Global Climatology: global distribution of climate-relevant constituents.
- Atmospheric Dynamics: stratospheric transport exchange between troposphere and stratosphere.
- Upper Tropospheric Chemistry: correlation of gas distribution with human activities.

The instrument is designed to allow simultaneous measurement of more than 20 relevant trace gases, including the complete NO_y family and several CFCs. Atmospheric temperature as well as the distributions of aerosol particles, tropospheric cirrus clouds and stratospheric ice clouds (including polar stratospheric clouds) are other important parameters that can be derived from MIPAS observations. These data will be obtained over the complete orbit, for all seasons and independent of illumination conditions, allowing measurement of the diurnal variations of the trace species. Atmospheric emissions will be measured at the Earth's horizon (limb) over a height range of 5 – 150 km. This observation geometry provides maximum measurement sensitivity and allows a good profiling capability to be achieved.

MIPAS will perform measurements in either of two pointing regimes: rearwards within a 35°-wide viewing range in the anti-flight direction, and sideways within a 30°-wide

Figure 10. The MIPAS viewing geometry



viewing range on the anti-Sun side (Fig. 10). The rearward viewing range will be used for most measurements, since it provides good Earth coverage, including the polar regions. The sideways range is important for observations of special events, like volcanic eruptions, trace-gas concentrations above heavily polluted areas, or concentration gradients across the dawn/dusk boundary.

MIPAS data products are calibrated high-resolution spectra, which are derived on the ground from the transmitted interferograms. From these spectra, such geophysical parameters as trace-gas concentrations, temperature profiles, mixing ratios, and global maps of atmospheric constituents can be retrieved.

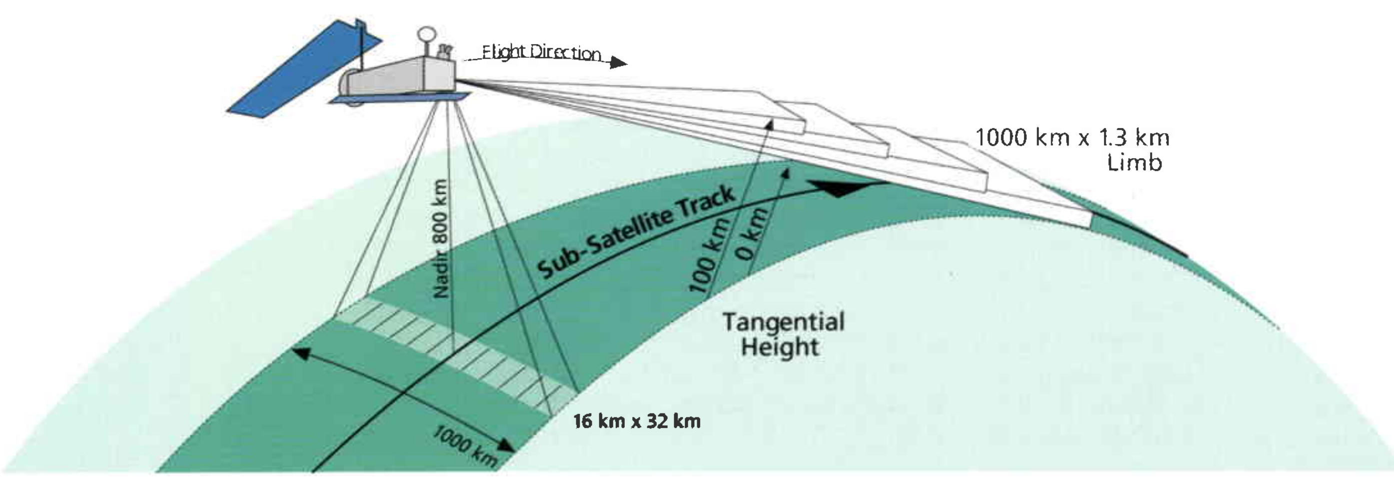
Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY)
The primary scientific objective of SCIAMACHY is the global measurement of various trace gases in the troposphere and stratosphere, which are retrieved from the instrument by observing the transmitted back-scattered and reflected radiation from the atmosphere in the wavelength range 240 – 2400 nm. This large range is also ideally suited for the determination of aerosols and clouds.

The nadir- and limb-viewing strategy for SCIAMACHY (Fig. 11) yields total column values as well as profiles for trace gases and aerosols in the stratosphere. This enables, in addition, estimates of global trace-gas and aerosol content and distribution in the lower stratosphere and troposphere.

The measurements obtained from SCIAMACHY will enable the investigation of a wide range of phenomena that influence atmospheric chemistry:
- in the troposphere: biomass burning, pollution, Arctic haze, dust storms and industrial plumes
- in the stratosphere: ozone chemistry, volcanic events and solar-proton events.

The scientific objectives are achieved by observing the atmosphere under different viewing angles. In nadir viewing mode, the global distribution (total column values) of atmospheric trace gases and aerosols will be observed. Cloud measurements will also be obtained. In this mode, the instrument is scanning across-track, with a swath width of ± 500 km with respect to the sub-satellite track. To obtain the altitude distribution of trace gases, SCIAMACHY performs limb observations over an altitude range of 100 km, with a vertical

Figure 11. The SCIAMACHY viewing geometry



resolution of 3 km. Nadir and limb observations are then interleaved to obtain dual observations over the 1000 km swath width.

Differential Optical Absorption Spectroscopy is applied in Sun and Moon occultation measurements, where either the Sun or Moon is tracked or a vertical scan over the complete solar or lunar surface is performed. The spectra obtained can then be compared with suitable calibration spectra to yield the differential absorption of the atmosphere.

The Altimetry mission

The Altimetry mission is fulfilled by the Radar Altimeter (RA-2), supported by three other instruments:

- the Microwave Radiometer, to correct for the wet-path atmospheric contribution
- the Laser Retro-Reflector, to allow precise ranging by ground laser stations and hence calibration of the RA-2 altitude
- the DORIS system(on-board receiver and on-ground beacon network), to provide a high-accuracy orbit.

Radar Altimeter 2 (RA-2)

RA-2 is derived from the ERS-1 and -2 Radar Altimeters, providing both improved measurement performance and new capabilities. The main objectives are the high-precision measurement of the time delay, power and shape of the reflected radar pulses to determine the satellite height and Earth-surface characteristics (Fig. 12). When operating over oceans, these measurements will be used to determine the ocean topography, thus supporting research into ocean-circulation, sea-floor and marine-geoid characteristics. The processing of the radar echo power and shape enables the determination of wind speed and significant wave height in the observed sea area, thereby also supporting weather and sea-state forecasting. In addition, RA-2 is able to map and monitor sea ice and polar ice sheets.

The new features of RA-2 enable it to extend the measurements of altitude and reflectivity over land. They will be used for the determination of surface elevation, geological structure and surface characteristics. RA-2 transmits radio-frequency pulses, which propagate at approximately the speed of light. The time elapsed from the transmission of a pulse to the reception of its echo reflected from the Earth's surface is proportional to the satellite's altitude. The magnitude and shape of the echoes contain information on the characteristics of the surface that caused the reflection.

On board the satellite, RA-2 measures the power level and time position of the samples from the earliest part of the echoes from ocean, ice and land surfaces. This is achieved using one of the new features on RA-2: a model-free tracker in the on-board signal processor that keeps the radar echoes within the sampling window. Window position and resolution are controlled by algorithms developed to suit the tracking conditions. Adaptive height-resolution operation is implemented by selecting the bandwidth of the transmitted pulses. As a result, measurements over the ocean are carried out at the highest resolution. Tracking is maintained over land, ice or during transitions from one kind of surface to another, sometimes by accepting a certain degradation in height resolution. Accurate altitude measurements over the ocean at the main frequency of

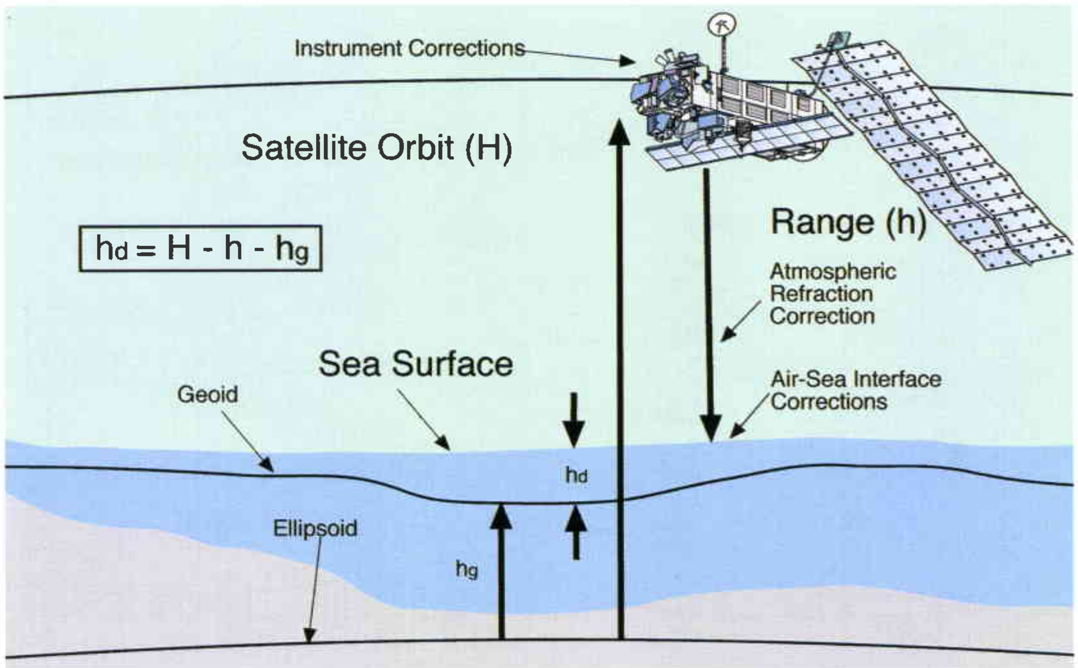


Figure 12. RA-2 derived height measurements

13.575 GHz are affected by fluctuations in the ionosphere beneath the satellite, but measurements in a second channel at 3.2 GHz enable those errors to be corrected.

The Laser Retro-Reflector (LRR)
The Laser Retro-Reflector (a passive device composed of nine reflective corner cubes) is mounted on the nadir-pointing face of the satellite close to the RA-2 antenna. An identical design was flown on the ERS satellites. The LRR will be used as a reflector by ground-based laser-ranging stations to provide precise ranging data, which will be correlated with RA-2 and DORIS data for calibration purposes.

The Microwave Radiometer (MWR)
The MWR's main role is the measurement of atmospheric humidity as supplementary information for tropospheric path correction of the Radar Altimeter signal, which is influenced both by the integrated atmospheric water-vapour content and by liquid water. In addition, MWR measurement data will be useful for the determination of surface emissivity and soil moisture over land, for the surface-energy budget investigations to support atmospheric studies, and for ice characterisation.

The MWR instrument is a derivative of the radiometers used on the ERS-1 and -2 satellites. It is a dual-channel, nadir-pointing Dicke-type radiometer, operating at frequencies of 23.8 and 36.5 GHz. Differential measurements have to be performed at two frequencies in order to eliminate the Earth's radiation.

Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS)
DORIS is an orbit-determination system that provides satellite orbit data with accuracies in the order of centimetres. In conjunction with the Radar Altimeter, DORIS will contribute to climatology studies by measuring spatial and temporal ocean-surface topography changes and variations in ice coverage.

DORIS is based upon the accurate measurement of the Doppler shifting of radio-frequency signals transmitted from ground beacons and received on-board the satellite. Measurements are made at two frequencies: at 2.03625 GHz for precise Doppler measurements, and at 401.25 MHz for ionospheric correction of the propagation delay.

DORIS will allow the determination of Envisat's position with an accuracy of better than 0.05 m radially, and its velocity with an accuracy of better than 0.4 mm/s. The DORIS system comprises the on-board instrument, a beacon network, the DORIS Control and Data Processing Centre and a network of more than 55 ground beacons deployed around the world (Fig. 13).

The mission-operations scenario

Payload data recording and transmission
Envisat has both global and regional mission objectives. The regional mission is constituted by the ASAR operating in its high-rate modes and MERIS in its full-resolution mode. These data will be acquired on a regional basis to meet specific user requests, as well as to build

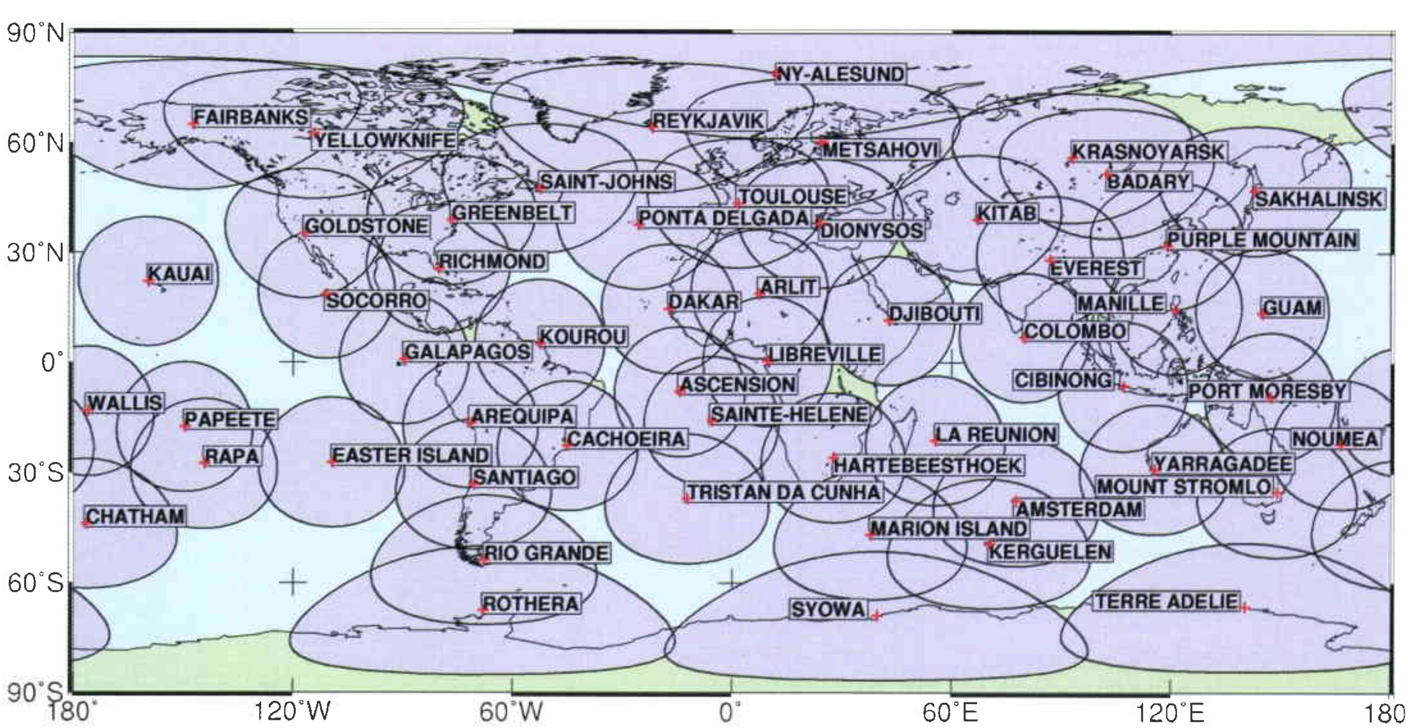


Figure 13. The DORIS ground-beacon network

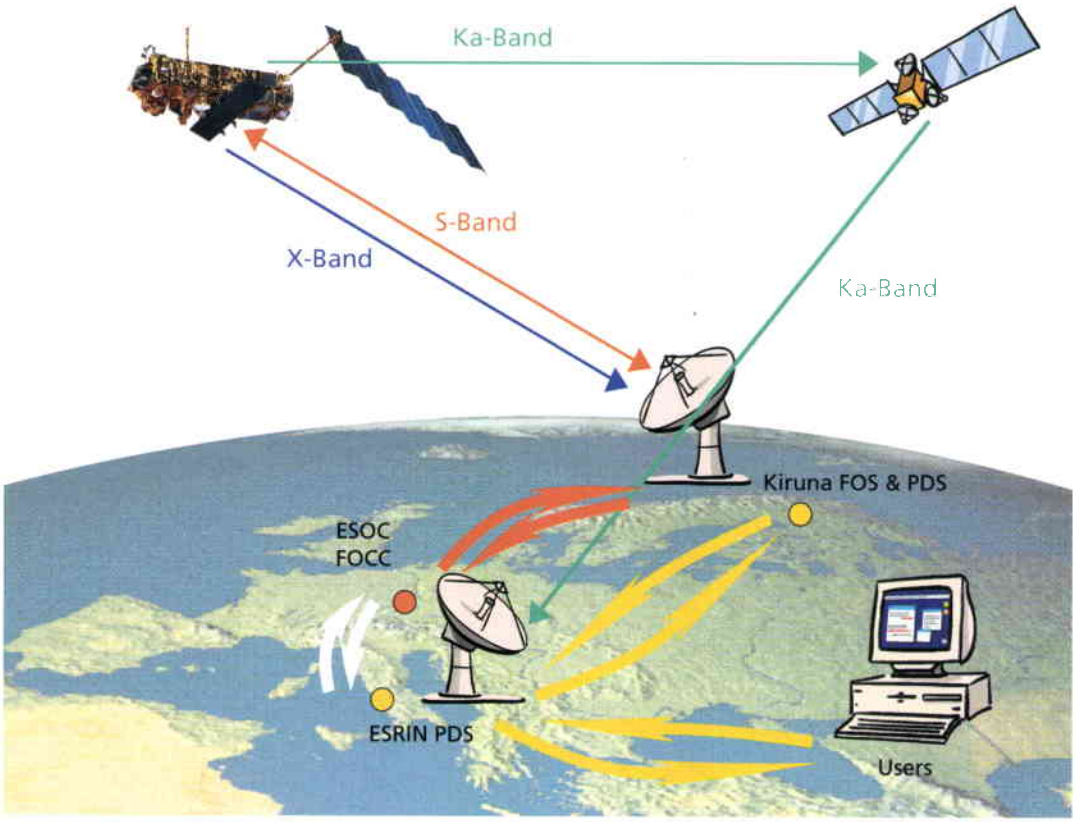


Figure 14. The Envisat system

up a reference data archive, following a background data-acquisition plan. All other instruments, including the low-rate modes of ASAR and MERIS, constitute the global mission, with instruments operated on a continuous basis around the orbit (for the MERIS low-resolution mode, this is limited to the 43 min Sun-illuminated part of the orbit).

For payload data recovery, Envisat is equipped with direct X-band links to ground stations as well as with Ka-band links relayed via ESA's geostationary data-relay satellite Artemis. The requirement for global coverage implies the use of on-board data storage, and so the satellite is equipped with two 70 Gbit solid-state recorders, and a 30 Gbit tape recorder as a backup. The solid-state recorders will permit:

- Complete global data collection (the 4.5 Mbps composite data stream), with data dumping once per orbit when in view of an ESA station (X-band at Kiruna, or Artemis satellite data-relay link to ESRIN).
- Recording of ASAR and MERIS high-rate data on a regional basis, when not within X-band station or Artemis visibility.

To downlink the stored data within the minimum ground-contact time, playback rates of 50 and 100 Mbps are provided. For the downlinking of the different categories of measurement data, the following channels (each transmitting 100 Mbps) are available:

- one X-band channel used for recorder dumps and the real-time transmission of MERIS full-resolution data
- one X-band channel for ASAR high-rate measurement data, or alternatively high-rate dumping of recorded regional data.
- two Ka-band channels, with the same data allocation as for X-band, for transmissions via Artemis.

Payload data-recovery scenarios

There are two data-recovery scenarios:

- the baseline scenario, sharing the workload equally between the Kiruna station, receiving the X-band links, and ESRIN, receiving the Ka-band links relayed via Artemis
- the back-up scenario, in case of unavailability of Artemis, making use of X-band links only, but ensuring full data recovery via the Kiruna station (for 9 to 10 orbits per day) and the Svalbard station (for the remaining 4 to 5 orbits per day).

In both scenarios, recorded-data dumps will be performed only in visibility of the ESA stations, and X-band direct transmission of regional data will only be provided in visibility of stations having a valid licence. Both scenarios allow the global as well as the regional mission objectives to be fulfilled.

The Ground Segment

The Ground Segment, which provides the means and resources needed to efficiently manage and control the satellite operations and the provision of user services, has two major elements:

- the Flight Operations Segment (FOS)
- the Payload Data Segment (PDS).

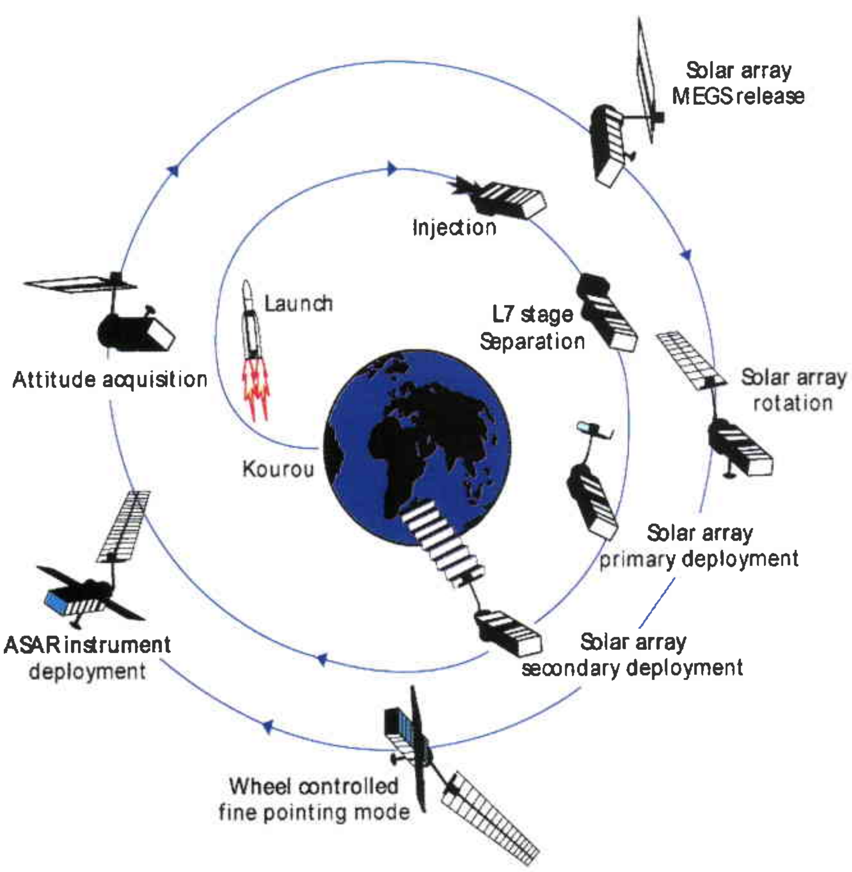
Flight Operations Segment (FOS)
The FOS is composed of the Flight Operations Control Centre (FOCC), located at ESOC in Darmstadt (D), and the associated command and control stations. It will control the satellite throughout all mission phases, including:
- satellite operations planning
- mission planning interface with Artemis
- command and control of the satellite
- up-loading of operation schedules on a daily basis via the TT&C station at Kiruna-Salmijärvi.

Furthermore, the FOCC will support:
- satellite configuration and performance monitoring
- software maintenance for the spacecraft and payload elements
- orbit prediction, restitution and maintenance.

Satellite command and control will nominally be performed using the two command and control stations of Kiruna-Salmijärvi and Svalbard. The Kiruna-Salmijärvi station is the primary control station for 9 to 10 consecutive orbits per day, and the remaining 4 to 5 orbits per day will be accessed via the Svalbard station. For the Launch and Early Orbit Phase (LEOP), 7 extra stations will supplement the network to ensure good coverage of the critical events (Fig. 15).

The FOCC prepares the satellite operation plans based upon a fixed strategy defined for the global mission, and operation requests received from the Payload Data Control Centre (PDCC) for the regional mission. It also plans the Artemis-related operations and interfaces with the Artemis mission-planning facilities.

Figure 15. LEOP critical events



The FOC facilities are based on an upgrade of ESOC's well-proven SCOS-1B system used for the two ERS missions. This upgrade has been performed with successive deliveries allowing a stepwise acceptance and validation process. A satellite simulator, emulating Envisat's on-board software, supports operational-procedure validation and FOCC operator training. The flight-dynamics software, derived from the ORATOS system already in use for ERS, has been upgraded to support star-tracker control and monitoring. The orbit-prediction, orbit-restitution and orbit-control/manoeuvre-planning activities will be performed as for ERS, with the same software and in-orbit control strategy.

Payload Data Segment (PDS)
The PDS comprises all of those elements related to payload data acquisition, processing and archiving, as well as those concerning the user interfaces and services. It will thus provide:
- all payload data acquisition for the global mission
- regional data acquisition performed by ESA stations
- processing and delivery of ESA Fast Delivery Products
- data archiving, processing and delivery of ESA offline products, with the support of the Processing and Archiving Centres (PACs)
- interfaces with national and foreign stations acquiring regional data
- interfaces to the user, ranging from order handling to product delivery.

The PDS centres and stations will be co-ordinated by the PDCC located at ESRIN, in Frascati (I). The PDCC will interface with the FOCC for all mission-planning activities. The PDS ESA stations include:
- the Payload Data Handling Station (PDHS-K), located at Kiruna-Salmijärvi (S), providing X-band data reception
- the PDHS-E, located at ESRIN, receiving via a User Earth Terminal (UET) data relayed by Artemis (Fig. 16)
- the Payload Data Acquisition Station (PDAS), located at Fucino (I), providing direct X-band data reception for the regional mission and offering, together with the Kiruna station, coverage of Europe and the Mediterranean basin.
- the PDHS-S, located at Svalbard (N) and used when Artemis is not available, to complement the Kiruna PDHS for ensuring the recovery of all payload data dumps.

The PDCC builds up satellite observation scheduling based upon user requests, and provides it to the FOCC for satellite operations planning. With its four stations, the PDS acquires all payload data directly, or in deferred mode via on-board recorder data dumps. They are processed in Near Real Time (NRT), to provide users with a complete suite of products within 3 h of an observation being made. For this purpose, all operating strategies, with or without Artemis, ensure that the data stored on-board are dumped every orbit within the visibility of one of the ESA PDS stations. For providing offline products, the PDS relies on the Processing and Archiving Centres (PACs), implemented with national funding by the Participating States. The ESA PDS centres and stations are being provided via a single Envisat PDS procurement action, led by Alcatel.

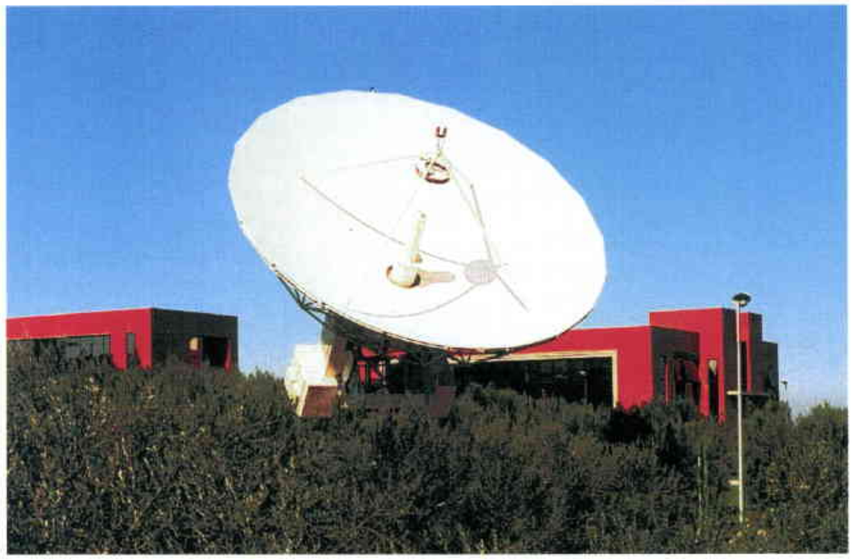


Figure 16. The Artemis User Earth Terminal antenna at ESRIN, in Frascati (I)

Offline Centres providing Level-1b and -2 Products

LRAC	Low-Rate Archiving Centre for all Level-1b global mission products	at Kiruna-Salmijarvi (S)
D-PAC	All atmospheric products (with FMI for GOMOS) and ASAR*	at DLR, Oberpfaffenhofen (D)
F-PAC	RA-2, MWR and Doris Orbit products	at CNES, Toulouse (F)
I-PAC	ASAR and MERIS FR products*	at ASI, Matera (I)
E-PAC	MERIS FR products*	at Maspalomas (E)
S-PAC	MERIS RR products, co-located with the LRAC	at Kiruna-Salmijarvi (S)
UK-PAC	AATSR and ASAR*	at NRSC, Farnborough (UK)

* For ASAR and MERIS FR, archive and offline services are shared between several PACS

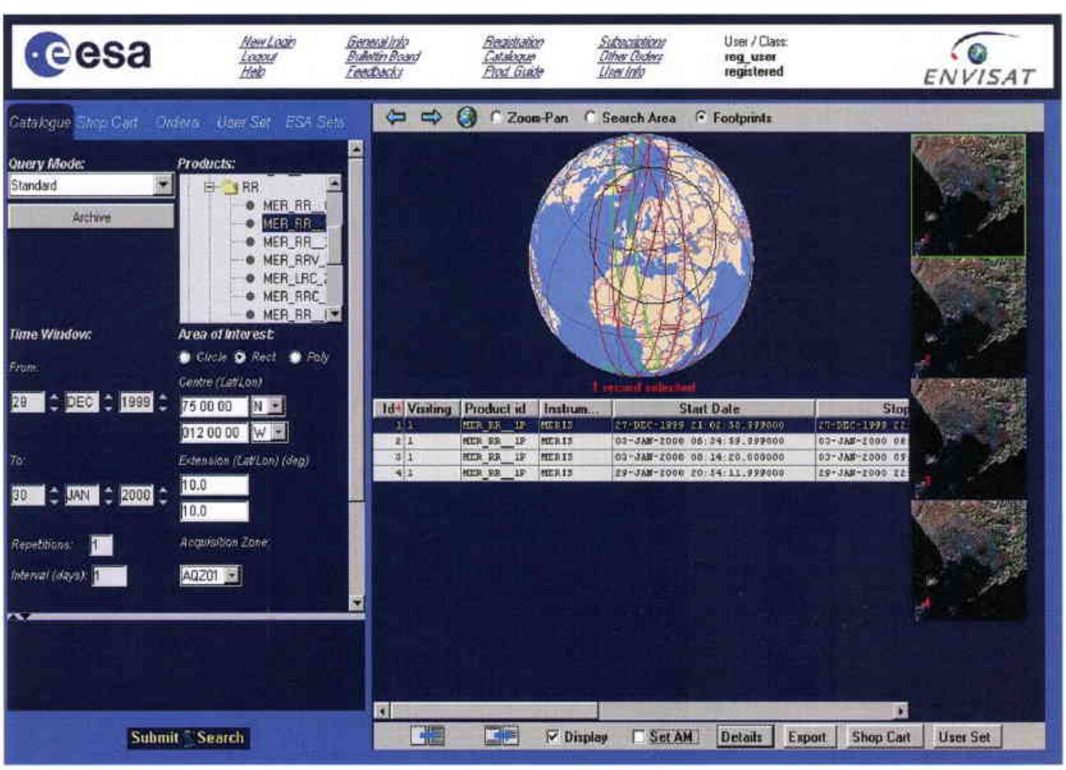


Figure 17. A typical user screen

Since the PACs are providing offline ESA products based upon the same processing algorithms as the NRT products, the PACs are requested to use the facilities developed for the PDS. These facilities are made available to them as generic elements, with each PAC procuring its computer hardware setup, on which the generic elements are installed, to build up the specific configuration required to fulfil its assigned tasks. With this approach the users get, for each instrument, a single suite of coherent NRT and offline products. ESA is committed to guarantee, with the support of Expert Support Laboratories (ESLs), continuous calibration and validation of the PDS products throughout the mission's lifetime, as well as processing-algorithm upgrades as required. Consequently, only one set of processors will be maintained and upgraded, ensuring coherency of all the user PDS services, whilst at the same time minimising the corresponding overall maintenance costs.

User services
The user services offer, via Internet:
- a unified user interface, search mechanism and ordering interface, without the need to know where the data are physically stored, since all stations and centres are linked by a PDS internal network (ordering of products requiring specific data acquisition will be routed to the PDCC)
- on-line browsing for all imaging instruments and the possibility of obtaining direct on-line delivery of small products
- ordering on a subscription basis for the systematic delivery of selected product type(s) in NRT or off-line.

The Internet user screen is illustrated in Figure 17.

The on-line product data dissemination will benefit fro the use of ground lines as well as of a dedicated Data Dissemination System via satellite over Europe, offering a sustained rate of 2 Mbps, 24 hours per day, for data reception by very small DVB terminals.

Figure 18. PDS data-product samples already produced

PDS products and validation activities
ESA is committed to provide, with the PDS, a complete suite of Level-1b products and a comprehensive set of Level-2 products. Level-1b products are geo-located data products providing engineering quantities directly derived from the instruments: radiance, reflectance, transmittance, polarisation, radar back-scattering values, and radar echo-time delay. These products are presented as images for ASAR, MERIS and AATSR.

All Level-1b products will be calibrated during the in-orbit Commissioning Phase. Various techniques will be involved, using on-board calibration devices and/or specific modes of the instruments to observe targets in the sky (Sun, Moon, stars) or on the Earth (natural stable targets, like deserts or tropical forests, as well as specially developed targets like transponders or radar corner-reflectors).

Level-2 products will provide geophysical variables obtained by processing the Level-1b products further using validated geophysical algorithms. Level-2 products will provide quantitative values for atmospheric variables (temperature, pressure, atmospheric constituents, aerosol and cloud parameters) as well as marine variables (ocean surface winds and waves, ocean and coastal-zone water constituents, sea-surface temperature), and land variables (vegetation indices, temperatures, pressures and reflectances).

For each geophysical data product, a specific validation is required. It will be performed by correlating the obtained data products with various in-situ measurements using ground-based, airborne and balloon-borne instruments. In addition, comparisons will be performed with other satellite data as well as analyses based on the use of data assimilation models (meteorology, climatology, etc.).

Samples of these products (Fig. 18) have already been produced and distributed to the users for familiarisation purposes.

Before the end of the Commissioning Phase, all of the Level-1b products will be released as calibrated products. Most of the Level-2 products will be released with notification to the user of the corresponding confidences and error bars. For products obtained from Envisat instruments having an ERS heritage, the validation will be performed within 6 months of launch. That for the novel instruments such as MERIS and the three atmospheric instruments will take somewhat longer.

Data policy

The Envisat Data Policy, illustrated in Figure 19, defines two categories of use:

- Category-1 use: for research and applications development
- Category-2 use: for operational and commercial use.

For Category-1 use, 700 proposals, including 130 proposals to support product validation, have been selected in response to an Announcement of Opportunity issued by ESA in 1998. Category-1 users will be served directly by the ESA PDS. For Category-2 users, two worldwide distributors have been selected: SARCOM, led by Spot Image, and EMMA, led by Eurimage. Some niche distributors have also applied for specific licences, in accordance with the provisions laid down in the approved Envisat Data Policy. The PDS services and data products will be available to all distributors.

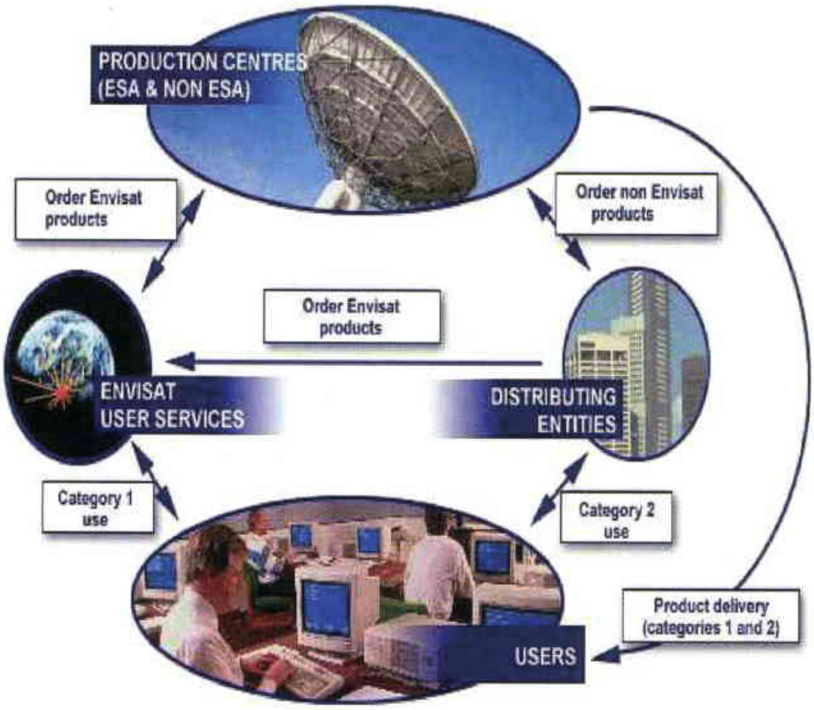


Figure 19. The Envisat Data Policy's implementation

Conclusion

With the Envisat Programme, European space industry and the scientific community supporting the Programme are reinforcing Europe's position at the leading edge of Earth-observation technology and services, following up the successful ERS missions. Given its sheer size, the Envisat development programme has required the involvement of almost all of Europe's space industries in the development of numerous advanced technologies, particularly for the payload.

The mission is attracting very great interest in the Earth-science community, both at European level and worldwide. This was demonstrated conclusively by the response to the Announcement of Opportunity for Envisat data exploitation and the large involvement of scientists in the preparation of the product-validation activities for the in-orbit commissioning phase.

Ariane-5 is set to inject Envisat directly into its Sun-synchronous orbit in Autumn 2001. After the few weeks required to get the satellite and its payload operational and to set up the various data-recovery links, the main challenge remaining will be to complete the Commissioning Phase and to achieve, within its tight schedule, the timely availability of the engineering calibrated and geophysically validated data products. Envisat should then respond very well to the high expectations of the users and provide them with reliable data products for at least the nominal five-year lifetime of the satellite.

Acknowledgement

The extremely ambitious development of the Envisat space segment has been successfully achieved thanks to the skilled and sustained support received, over almost ten years, from the European space industry teams led by Astrium Ltd. And Astrium GmbH.

Thanks also go to Alcatel Space for leading the challenging development and integration of the Payload Data Segment (PDS), which is the most comprehensive Earth-observation ground segment ever built. This venture would not have succeeded without the brilliant contributions of the Expert Support Laboratories, all over Europe and in Canada, in developing the processing algorithms for the instrument products implemented in the PDS.

Finally, my great thanks go to the ESA teams at ESTEC, ESOC and ESRIN for their dedication to the Envisat Programme and their great team spirit. The availability and complementary expertise of these teams has been essential to the achievements so far, as well as for the challenging tasks that still lie ahead with the final launch preparations and the planned in-orbit activities.

The Envisat Satellite and Its Integration

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For the early years of this new millennium, Envisat is ESA's major contribution to the study of the Earth as a system. Carrying ten sophisticated instruments – both optical and radar – it is the largest and most complex satellite ever built in Europe. It has been designed and tested over a period of more than 10 years. Much of the integration and test programme was conducted on site at ESTEC, in Noordwijk (NL). It will be the first satellite launched into a polar orbit by Ariane-5.

This article summarises the design and engineering of Envisat, and explains the model philosophy and test approaches used. The launch campaign plans are also briefly described.

Introduction

Envisat is the largest and most complex free-flying satellite ever built in Europe. It will carry a comprehensive series of instruments designed to observe a whole series of interrelated phenomena that characterise the behaviour of the Earth's environment as a system. The satellite, together with its related ground systems, will continue and extend the data services provided by the Agency's earlier ERS-1 and ERS-2 satellites. In particular, Envisat should substantially increase our knowledge of the factors determining our environment. It will make a significant contribution to environmental studies, notably in the areas of atmospheric chemistry and ocean studies, including marine biology.

The satellite makes use of the multi-mission capability of the Polar Platform originated in the Agency's Columbus Programme. This development also forms the basis for MetOp. The Polar Platform in turn has drawn heavily on the equipment and technologies developed within the framework of the French Spot programme. Almost all of the instruments on the satellite have been specifically developed for Envisat, with one or two having a strong design heritage from ERS.

The observations made by Envisat will eventually be continued and extended by a series of new, smaller satellite programmes being initiated within the Agency's Earth Observation Envelope and Earth Watch Programmes.

Background

The Columbus Programme approved at the ESA Ministerial Council Meeting in The Hague in 1987 included the development of a multi-mission Polar Platform as part of the International Space Station. Following a series of studies and iterations with potential users, an implementation re-using the equipment and architecture of the Spot-4 spacecraft bus design, although with a significantly enlarged structure, was decided upon. The main development phase (Phase-C/D) for the Polar Platform programme was awarded to British Aerospace in Bristol (UK) – later to become Matra Marconi and now Astrium Ltd. – in late 1990.

Meanwhile, in the Earth Observation area, the Agency was considering, as ERS-1 grew closer to launch, how to continue and extend the services offered. In 1988, these elements were drawn together in an ESA proposal to its Member States for an overall 'Strategy for Earth Observation'. These considerations led to the adoption of the POEM-1 programme, using the Polar Platform, at the Ministerial Council Meeting in Munich in November 1991. There continued to be an evolution in the payload complement for POEM-1. This culminated in a splitting of the payload into separate Envisat and MetOp satellites, which was finally agreed at the next Ministerial Council in Granada in November 1992. A Phase-C/D contract for the procurement and support of the Envisat payload (the so-called 'Mission Prime Contract') was awarded to Dornier Satellitensystem, now Astrium GmbH, in July 1992.

As a result of the programmatic origin of the satellite, there remain two large contracts for its implementation:
- the Polar Platform Prime Contract (Astrium Ltd.), and
- the Mission Prime Contract (Astrium GmbH).

These two large contracts, interfacing with each other at some of the technically most critical on-board locations, caused a number of problems during the development programme. The satellite integration programme has, however, largely been carried out at ESTEC following the closure of Astrium's Bristol site. As a result, many of the technical personnel have been collocated (with ESA) at ESTEC. This, and the grouping of both contractors within the Astrium company, has ensured a much smoother technical path for the programme in its final phase.

The organisation of the Agency's project teams initially also reflected the programmatic split, with separate project divisions for Polar Platform and payload. More recently the project teams have been merged within a single division. This too has simplified the technical conduct of the programme.

Major capabilities
The satellite is designed for a Sun-synchronous polar orbit (Table 1). The planned operating altitude is 800 km, although a range of altitudes can be selected allowing variations in the repeat cycle of the ground track. The local time at the equator for the descending node has been selected as 10.00 a.m., which optimises illumination conditions for part of the optical payload.

The selected orbit has a repeat cycle of 35 days and an orbital period of 100.6 min. Its inclination is 98.54 deg, which implies small, uncovered areas at the poles for instruments with limited swath widths. The on-board systems allow the ground track to be maintained within 1 km and the local hour to within 5 min. One of the on-board instruments (DORIS), when used in conjunction with a dedicated set of ground stations, provides real-time knowledge of position to within 50 cm, and a precision altitude restitution to within 5 cm.

In nominal operations, the satellite is pointed using star trackers in a 'stellar yaw-steering mode'. In this mode, the satellite is yawed to compensate for the apparent motion of the Earth across-track beneath the satellite. This compensation simplifies the processing of Doppler signals from the synthetic-aperture radar. When using the star trackers, random pointing errors will be less than 0.0085 deg, and the stability over all periods of up to 170 s better than 0.015 deg. Attitude estimation will be better than 0.04 deg. This pointing performance allows both adequate geographical location for data measured on the Earth's surface, and a vertical resolution when viewing the atmosphere at the limb of better than 3 km.

The satellite provides an average of 1900 W for instrument operations through sunlit and eclipse portions of the orbit. This enables all instruments except MERIS and ASAR to be operated continuously throughout the entire orbit. MERIS, the Medium-Resolution Imaging Spectrometer, requires sunlight to operate. ASAR, the Advanced Synthetic-Aperture Radar, produces such enormous quantities of data in its high-resolution mode that its operation is limited to 30 min per orbit.

Table 1. Major capabilities of Envisat

- Sun-synchronous orbit: 800 km, 10 a.m. descending node, 35-day repeat cycle
- Stellar yaw steering, for accurate pointing and Doppler compensation of SAR
- 1900 Watts, 2500 kg for instruments
- Data recovery at up to 100 Mbps direct via X-band or via Artemis
- On-board storage in solid-state recorders for regional and global missions
- S-band command and control; 2 kbps uplink, 4 kbps downlink

The data-handling capabilities of the spacecraft have also been sized to support the global and regional missions. All instruments except MERIS and ASAR operate continuously, together producing 4.6 Mbps. There are separate additional regional missions for MERIS (up to 25 Mbps) and ASAR (up to 100 Mbps). On-board storage in redundant solid-state recorders allows the recording and dumping of all data from the global and regional missions. Data can be downlinked directly when overflying a suitable ground station, such as Kiruna in Sweden, via a fixed X-band antenna, or when within visibility of Artemis, via a steerable Ka-band antenna.

Command and control of the satellite and payload is via an S-band transponder. The satellite will normally be operated by uplinking a 24-hour command timeline. Housekeeping data is available in real time when over a ground station, but is also included in the global mission data stream.

The satellite is designed for launch only by Ariane-5. It has a total launch mass of 8100 kg, of which 2150 kg are instruments. The physical size of the spacecraft requires the Ariane-5 long fairing, for which Envisat is the first customer.

Major components

The satellite is made up of two major sub-assemblies, the Service Module (SM) and the Payload Module (PLM), with a simple structural, electrical and avionics interface between them. All instruments are physically located on the PLM, to which the instruments have a largely standardised interface. The modularity of the design has made it possible to conduct by far the majority of the integration work on the SM, PLM and instruments in parallel.

Service Module

The SM provides the standard satellite support functions, and was subcontracted to Astrium SAS. It is based on the design of the Spot Mk-II service module, but with a number of important new developments, particularly in the structure and solar-array areas (Fig. 1).

Figure 1. The Envisat Service Module being readied for shock testing in the ESTEC facilities

The SM includes eight batteries, and the solar array. This is a flat-pack array designed for the Polar Platform by Fokker Space (NL), based on their standard design elements. Once deployed, the array is rotated to point continuously towards the Sun using a solar-array drive mechanism, which is attached to the base of the central cone.

The propulsion module on top of the cone contains four tanks, which hold 300 kg of hydrazine.

A single central computer containing both command and control and AOCS functions performs on-board data management. It controls the SM equipment via a standard on-board data-handling bus. The central computer also communicates with the central computer of the PLM via the same bus.

Payload Module

The PLM (Fig. 2) provides the physical accommodation for the instruments, as well as a range of instrument-related services, such as power switching, integrated payload command and control, data storage and downlinking. In addition, some equipment that would logically be part of the Service Module is physically located on the PLM for performance reasons. Such equipment includes the star sensors, the gyroscopes, and some of the thrusters.

Within the Earth-pointing and side compartments of the PLM is the Payload Equipment Bay (PEB), which contains both payload-support and instrument equipment. Astrium GmbH is the subcontractor responsible for the provision of the PEB equipment for the Polar Platform, and the design of this subassembly is based on their experience with ERS-1 and ERS-2.

Measurement data generated by the instruments is processed by a High-Speed Multiplexer (HSM) for recording or transmission direct to ground. Low-rate data (0 – 32 Mbps) are routed from the instruments to the HSM to create data streams that are passed to the recorders or to the Encoding and Switching Unit (ESU) prior to transmission. The high-rate (100 Mbps) data from the ASAR in Image Mode is introduced directly to the ESU and modulates the two 50 Mbps channels of the downlink.

Each of the two redundant Solid-State Recorders can be flexibly used to simultaneously store data from the global composite at 4.6 Mbps and from the regional missions. The communications subsystem for the transmission of instrument data or housekeeping telemetry comprises an X-band link direct to ground and a unidirectional Ka-band link via Artemis.

Figure 2. The Envisat Payload Module on the payload integration stand at ESTEC

Instruments
The roles and functions of each of the Envisat instruments are described elsewhere in this issue of the Bulletin, but some information on their accommodation is relevant to an understanding of the satellite as a whole.

There are a total of ten instruments embarked on the satellite, although one of them, the Laser Retro Reflector, is entirely passive. Two others, DORIS and the Microwave Radiometer, share a single Instrument Control Unit and are operated as though they were a single instrument. Tables 2 and 3 list the instruments, together with their primary mass and power requirements. Figure 3 shows how the instruments are accommodated on the deployed spacecraft.

Instrument procurement was via one of two routes. Instrument sub-contractors, working for the Mission Prime Contractor, designed and built the so-called 'ESA-Designed Instruments' (EDIs). A further three instruments were provided directly by national funding agencies

Table 2. ESA-developed instruments

ASAR	Advanced Synthetic-Aperture Radar	817 kg	1400 W (max)
RA-2	Radar Altimeter	110 kg	118 W
MWR	Microwave Radiometer	24 kg	22 W
GOMOS	Global Ozone Monitoring by Occultation of Stars	164 kg	157 W
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding	327 kg	196 W
MERIS	Medium-Resolution Imaging Spectrometer	209 kg	110 W
LR	Laser Retro Reflector	2 kg	Passive

Table 3. Announcement of Opportunity instruments

SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography	201 kg	121 W
DORIS	Doppler Orbitography and Radio-positioning Integrated by Satellite	85 kg	34 W
AATSR	Advanced Along-Track Scanning Radiometer	108 kg	94 W

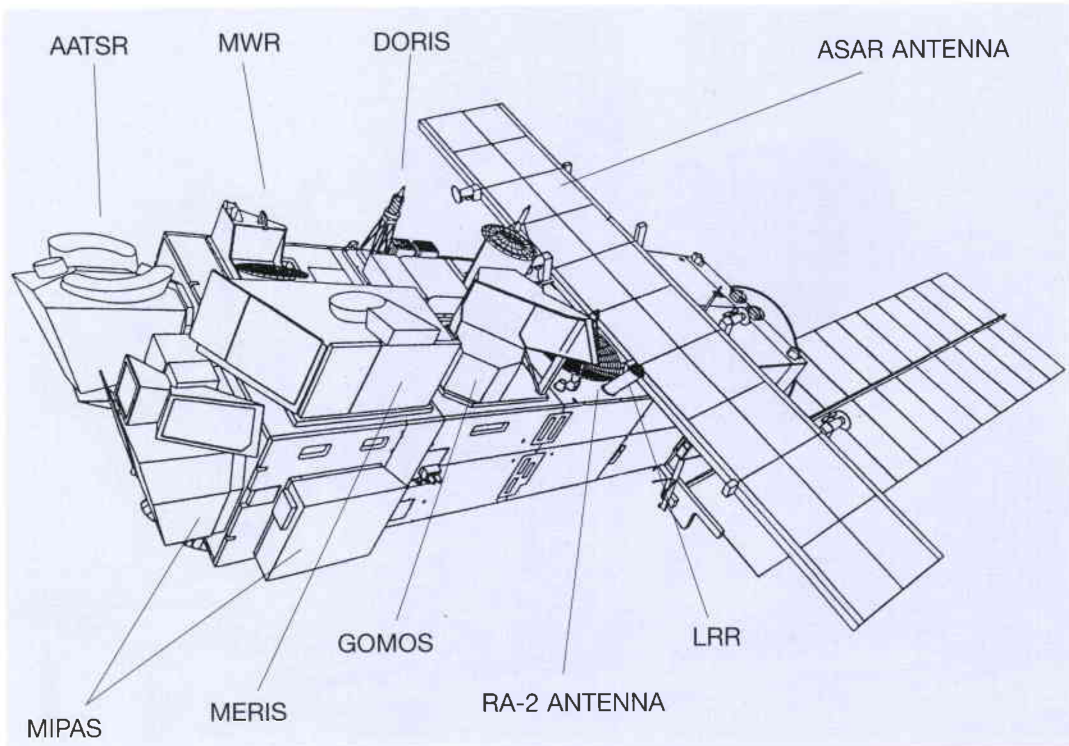


Figure 3. The flight configuration of the Envisat instruments; the SCIAMACHY instrument is behind AATSR

for integration with the Polar Platform. These are the so-called 'Announcement of Opportunity Instruments' (AOIs). The Mission Prime Contractor provided engineering and integration support for the AOIs.

With three exceptions, instruments are mounted entirely on the outside of the payload structure. This allows them maximum flexibility in terms of fields of view, both for observation and for thermal reasons. Externally mounted instruments are thermally decoupled from the Payload Module. Some units of RA-2, GOMOS and ASAR are mounted inside the PEB and share its thermal control.

Each instrument has a dedicated Instrument Control Unit (ICU) that interfaces to the Payload Module Computer (PMC) via a standardised avionics interface. The ICU is responsible for executing the macro commands sent from the PMC as their time tags become due.

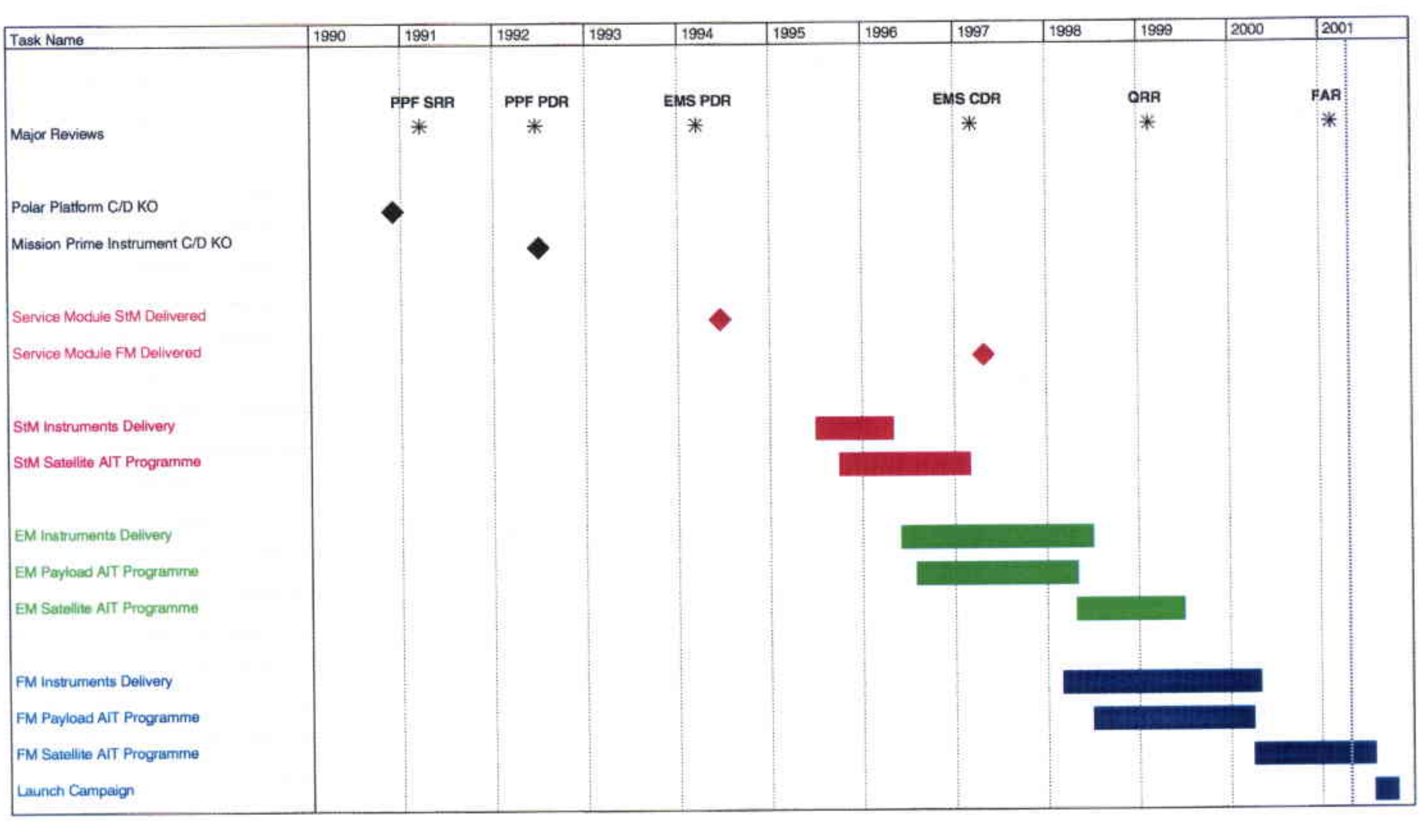


Figure 4. The major spacecraft campaigns

As a general principle, instruments were integrated, qualified and acceptance tested as a unit before delivery for integration with the Polar Platform.

Development programme

Model philosophy

The general philosophy for the satellite has been to use three models:

- A structural model for mechanical qualification, including static-load, modal-survey, shock, acoustic and sine testing.
- An engineering model for electrical compatibility testing, for preliminary operability demonstration, for debugging ground-support equipment, and for a preliminary demonstration of RF compatibility.
- A flight model for thermal-balance and thermal-vacuum testing, for acceptance acoustic and sine and qualification shock testing, for RF-compatibility acceptance and for conclusive demonstration of operability.

The duration of each of the major campaigns and their relationship to the programme reviews is shown in Figure 4.

This simple model philosophy was modified in significant ways as a result of the historical development of the programme. Table 4 lists the models built of each of the major satellite items.

An RF mock-up of the entire spacecraft was built at a very early stage in the programme to allow the measurement of likely coupling factors between transmitting and receiving antennas.

Since the electrical design of the Service Module was so similar to that of Spot, only two models of the Service Module were made: a structural model and the flight model.

For the solar array (Fig. 5), there was only one complete model, the flight model. In order to avoid overstressing, it was accepted together with the flight-model spacecraft. A single panel took part in the structural-model satellite campaigns. The majority of qualification was carried out at component level.

The instrument development programmes began nearly two years after the Polar Platform development programme. Consequently, a number of instrument suppliers had difficulty meeting need dates for full engineering-model instruments. In these cases simplified

Figure 5. The solar array under test at Fokker (NL)

Table 4. Component model characteristics

Component	Heritage	StM	EM	FM	Remarks
Service Module	Spot avionics New mechanics	Yes	No	Yes	EM Satellite programme with FM service Module
Payload Carrier	New	Yes	Form and fit only	Yes	FM refurbished STM structure
Payload Equipment Bay	New (ERS)	Mass Dummies	Yes	Yes	
Solar Array	Fokker product	One panel only	No	Yes	
Ka-band Assembly	New	Partly	Yes	Yes	

Table 5. Instrument-model characteristics

Instrument	Development Category	StM	EM	FM	Remark
ASAR	New	Antenna	Reduced EM	FM	4 active tiles for EM
GOMOS	New	No	Full EM	FM	Reduced EM to serve spacecraft EM
MERIS	New	Yes	Reduced EM	FM	1 out of 5 cameras (EM)
MIPAS	New	Yes	Full EM	FM	Reduced EM to serve spacecraft EM
MWR	Rebuild	No	No EM	FM	ERS-based instrument
RA-2	Partially new	No	Full EM	FM	ERS-based instrument
LR	Rebuild	No	No EM	FM	ERS-based passive optical system
AATSR	Partially new	No	Reduced EM	FM	ERS-based instrument
DORIS	Rebuild	No	Full EM	FM	EM available for spacecraft RFC test
SCIAMACHY	New	Yes	Reduced EM	FM	Reduced EM to serve spacecraft EM

instrument models were supplied sufficient for the real needs of the engineering-model satellite programme. In a number of cases, this allowed the instrument supplier to continue development work on a full engineering-model instrument, to the eventual benefit of the flight model. Table 5 lists the development models for each of the instruments.

The optics modules of SCIAMACHY and MIPAS were replaced during the flight-model thermal test with thermally representative models.

Satellite software development and validation approach

Envisat carries some 40 different real-time processors and a wide range of the satellite's functions are software-implemented: commanding and monitoring of SM, PEB and payload-instrument equipment, payload science data-handling functions, onboard time distribution and datation, and scientific data processing (in the case of the AOCS and of several payload instruments).

In general, these computers have used Ada as the programming language (e.g. the for Payload Module Computer), or Assembler when tight memory resources forced the designer to optimise the size of the code for a given function (e.g. for the Service Module Central Communication Unit). Most processors belong to the 1750 family (standard instruction set). The software is designed to schedule tasks in a cyclical manner where different tasks might be executed with different frequencies.

The development and validation of this software has been performed using development and validation platforms implementing a fully representative processor breadboard connected to a simulated environment modelling accurately all of the processor's interactions with its environment.

Most of the Envisat onboard software is either located in PROM and downloaded to RAM (e.g. most instrument software), or already loaded in RAM (in the case of the PMC). In most cases, software components are loadable and patchable by ground telecommands. To support this, the Flight Operation Segment at ESOC is equipped with a Software Maintenance Facility where software is modified, tests of the modified software are run, differences between the memory images extracted, and patch commands generated for uplinking. After uplinking, the updated memory is dumped for a final comparison within the software maintenance facilities.

There were difficulties associated with the initial design of the PMC software. Requirements stemming from the original Columbus multi-mission capability were never descoped to the specifics of the Envisat mission. At the same time, the separation between Mission Prime and Polar Platform Prime Contractors meant that proper requirements on mission operability were not levied on the PMC. These difficulties co-existed with a decision to use Ada on the late 1980s Mil Std 1750 processor the MAS 281.This situation led to late software modifications and additional validation effort. An independent company was contracted to perform additional intensive testing using four additional software-validation facilities. System-level schedule impacts were limited by tuning the scope of system tests to match successive and incremental deliveries of the PMC software for satellite Assembly, Integration and Testing (AIT). A mission time-line test simulating five consecutive orbits of intense satellite operation was successfully run in December 2000. The final version of the PMC software is currently completing non-regression testing.

System databases supporting in-orbit satellite operations

Two main database products have been delivered to support Envisat in-orbit operations:

- The Satellite Reference Database (SRDB) has been delivered by the Prime Contractor to ESOC to conduct in-orbit operations. It gathers together lower-level databases initially used within the various EGSEs, and ensures uniqueness of each parameter through a well-controlled nomenclature. The database as delivered to ESOC contains all macro commands to allow commanding of the satellite. It also contains all of the house-keeping parameters, their defined monitoring limits and the specific calibration curves that are required to monitor the satellite during the mission.
- The Satellite Characterisation Database was a deliverable from the satellite Mission Prime Contractor. It documents precisely, in a pre-agreed format, the results of all performance testing executed throughout the satellite development and validation phase. The contents of the database, such as alignment data or CCD spectral calibrations, have been used to build ground software for the generation of so-called 'Level-1b products' from each instrument.

Ground Support Equipment

The size and complexity of the spacecraft result in demanding requirements on ground-support equipment. Mechanical Ground Support Equipment (MGSE) includes conventional items such as a satellite trolley, vertical integration stands for the Payload and Service Modules, lifting beams for spacecraft and panels, and turnover trolleys. The satellite trolleys, of which there are two, to support two satellite models simultaneously, each weigh about thirty tonnes. They must be disassembled for transport and to move from one clean room to another. Even when disassembled, they are out-of-gauge items. Despite this, they are supported for movement on compressed-air pads hovering a few millimetres off the floor. This system works extremely well and the trolley is routinely manoeuvred by just two or three people.

The Electrical Ground Support Equipment (EGSE) is also large and complex, covering about 400 m^2 of floor area and consuming 0.1 MW. There are three principal elements:

- Service Module EGSE, including processors to stimulate AOCS sensors and special checkout equipment for · Service Module systems
- Payload Module EGSE, including special checkout equipment for payload subsystems
- Instrument EGSE organised around a single Integrated Test Assembly, but with a number of dedicated data and processing blocks for each of the instruments.

Each of these elements was based on standard systems using the Elisa checkout language procured from Astrium SAS (formerly Matra, Toulouse). Unfortunately, evolution of the standard between the procurement initiation for each of the elements meant that neither the software, nor the databases nor the hardware were interchangeable.

A significant and late addition to the EGSE was a pair of the Front-End Processors designed for the ground segment to ingest measurement data. These provide possibilities to realistically process every virtual channel data unit and every source packet, even at the highest data rate (100 Mbps). As a result, confidence in data integrity from every test is very high.

The EGSE used to test instruments was built around a standardised element, procured by the Mission Prime Contractor, which precisely simulated Polar Platform interfaces. The Integrated Test Assembly employed at satellite level used the same processor and software. This had two important benefits: time spent debugging the instrument EGSE was minimised by sharing resources, and the instrument-level test software could be used directly at satellite level.

A consequence of the number of processors involved in the EGSE has been lost test time due to hardware defects, design deficiencies and software bugs. The duration of the engineering-model campaign was significantly affected by resolution of these issues. It seems that when procuring EGSE, paying much more attention to system integrity and maintainability would have saved significant cost in the overall programme.

Launch campaign

Envisat will be the first user of the new S5 Payload Processing Facility in Kourou (Fr. Guiana). The launch team will occupy all of the available office space, all of the checkout areas, all of the integration room, and the smaller of the two fuelling halls.

About 340 tonnes of material will be transported to the launch site using a dedicated Antonov AN124 aircraft for the flight hardware, two Boeing 747s for the EGSE, and a ship for the MGSE items. At the peak, there will be about 120 project personnel supporting the launch campaign, which will last about three months. The MGSE will be set up by an advance party about a month before the start of the launch campaign itself.

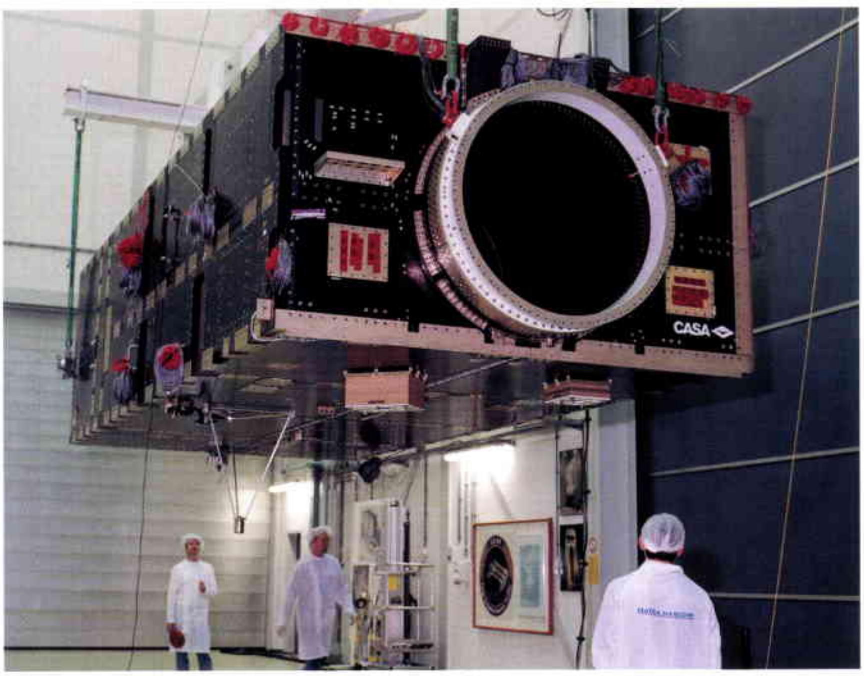


Figure 6. The Payload Module box structure around the central tube

Envisat's size made it impractical to design a container to fit the integrated satellite into the AN124, which is largest commercially available cargo aircraft. Consequently, the Service Module, Payload Module, ASAR antenna and solar array will be transported separately and the satellite reassembled in Kourou.

After assembly of the solar array, a test will be conducted to check that initiation of deployment functions correctly. A full electrical test of the spacecraft will take place, followed by fuelling with 300 kg of hydrazine. All of these activities will happen without leaving the class-100 000 facilities within the S5 building. The spacecraft will then be loaded into a special transport container for the short trip to the Final Assembly Building (BAF), where it will be lifted onto the top of the launcher and encapsulated in the fairing. Prior to encapsulation, the last of the remove-before-flight and install-before-flight items will be dealt with. There are more than 300 of these in total, so this operation will take place overnight. The assembled rocket with solid boosters attached and satellite mounted will then be transported to the launch pad, along a parallel pair of railway tracks, on the enormous launch table. Hopefully, the launch will take place at the very first launch opportunity, of which there is one per day.

Design and testing

Mechanical

Mechanically, the satellite consists of the cone of the Service Module, which at its lower end interfaces with the launcher and the central cylinder of the Payload Module. Shear panels attach sidewalls to form a stiff rectangular box structure. Figures 6 and 7 show the overall structure.

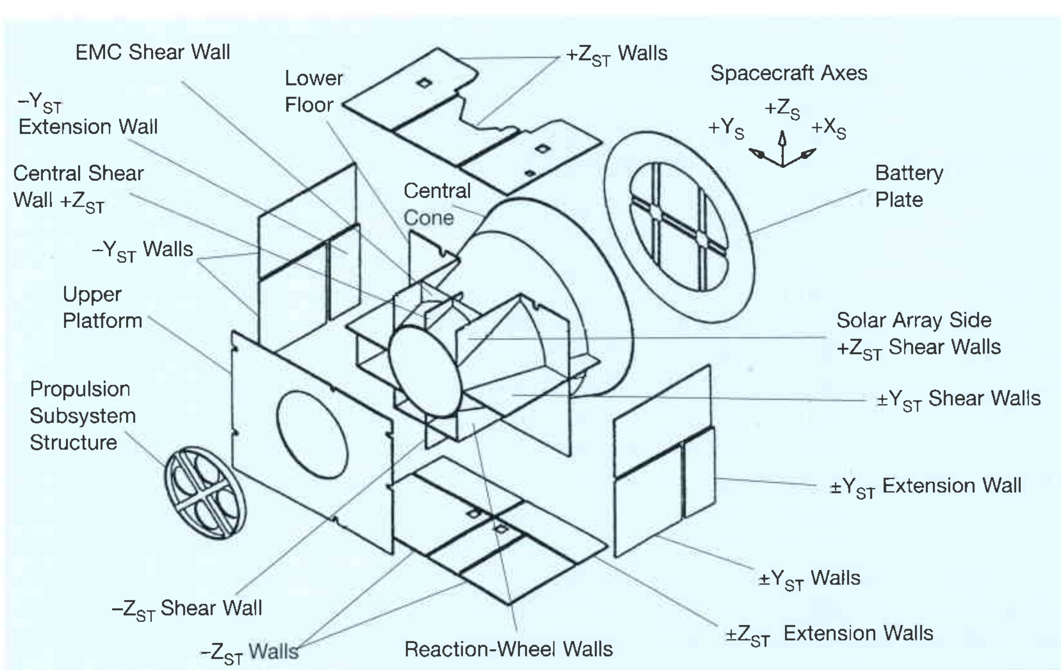


Figure 7. The Service Module's mechanical configuration

The SM is built around a CFRP cone as the primary structure, with a launcher interface at one end and the propulsion module at the other. Both interfaces are made of aluminium. A box-shaped metallic structure, with aluminium honeycomb panels, supports the electronic equipment and surrounds the central cone.

The structure of the Payload Module consists of a 1.2 m-diameter CFRP tube and a set of CFRP sandwich panels forming the webs and external faces of the PLM box. The structure is conceived as a stack of four bays, each 1.6 m high. The bay furthest from the SM (bay 4) is designed to be removable from the other three.

Static load tests were conducted using hydraulic jacks on separated structural models of the Service Module and the Payload Carrier. These tests involved loading the structure to the equivalent of 2.8g at its centre of gravity.

The structural-model satellite programme began with a modal-survey test that allowed the identification of modes, and their correlation with the satellite finite-element model. Following the test, the interface to the solar array was stiffened.

Sine vibration (Fig. 8) of this very large spacecraft brought a number of problems. The structural model was the first object to be tested on the new hydraulic shaker, HYDRA, at ESTEC. HYDRA allows simultaneous excitation of the test object with three translations and three rotations, although for Envisat only one axis was excited at a time. Even so, the satellite can be tested without a physical reconfiguration between axes, saving many days on the critical path. It also allows a complete set of very-low-level runs to be performed at the start of the test campaign, to identify early any unexpected behaviour of the new test object and to confirm the safety of the test. At the time of the structural-model test, the shaker's development was not complete, and so only the longitudinal axis was attempted, to avoid controllability problems in lateral. Even so, it was considered unsafe to test between 58 and 81 Hz. And qualification in this domain was achieved by a sine response analysis using the finite-element model qualified by the modal-survey test. Lateral axes on the structural model were tested on the electro-dynamic twin shaker also at ESTEC. The inertia of the test object meant, however, that instead of starting the sine scan at 5 Hz, it was started at 15 Hz. Qualification below 15 Hz was achieved using the results of the static load tests. Despite these difficulties, the structural-model test results were useful in refining the qualification and acceptance levels for both equipment and instruments

Figure 8. Envisat being installed on the HYDRA hydraulic shaker at ESTEC

For the flight-model acceptance test, the HYDRA had been much improved. Even so there were serious concerns about its controllability. There were also concerns about the effect of cross-talk from one axis to another on the validity of the test. An extensive series of pre-tests were performed using a dynamically representative dummy of Envisat. These showed quite serious cross-talk between axes and excitation of spurious frequencies. A strategy was adopted whereby cross-talk would be accepted, and deep notches to the base excitation predicted for launch accepted, provided all critical points were exercised above their flight limit loads at least once. In the event, the damping and linear behaviour present on the flight model (but not on the dummy) allowed the predicted base excitation to be achieved in all three axes with only one very minor deviation. A bonus was that the entire flight-model sine-vibration test was completed in just 7 days, compared to the three weeks or more predicted for the multi-shaker (Fig. 9).

To ameliorate the difficulties expected in identifying the mode shapes of the finite-element model in the results from HYDRA, a novel 'mini-modal-survey' test was performed. This test placed a single exciter at one of the lifting points of the satellite, and was executed in less than a day. The results provided a good identification of modes in the frequency range below 50 Hz. The required first lateral frequency for the satellite is above 5.5 Hz. The measured first frequency is about 7.8 Hz.

The design requirement from Ariane-5 is for a longitudinal quasi-static load of 4.55g and survival of 1g from 5 to 100 Hz. Lateral accelerations are below 0.8g up to 100 Hz. In common with most large space structures, extensive notching was necessary to protect sensitive items, such as the solar array, the ASAR antenna, and several of the optical instruments.

The vibration spectra (Fig. 9), which were accepted by Arianespace on the basis of coupled dynamic analysis, were less than 0.3g in longitudinal and less than 0.35g in one lateral axis from 35 to 100 Hz. The other lateral axis (in the plane of the Earth-pointing face) was less than 0.6g in the same region.

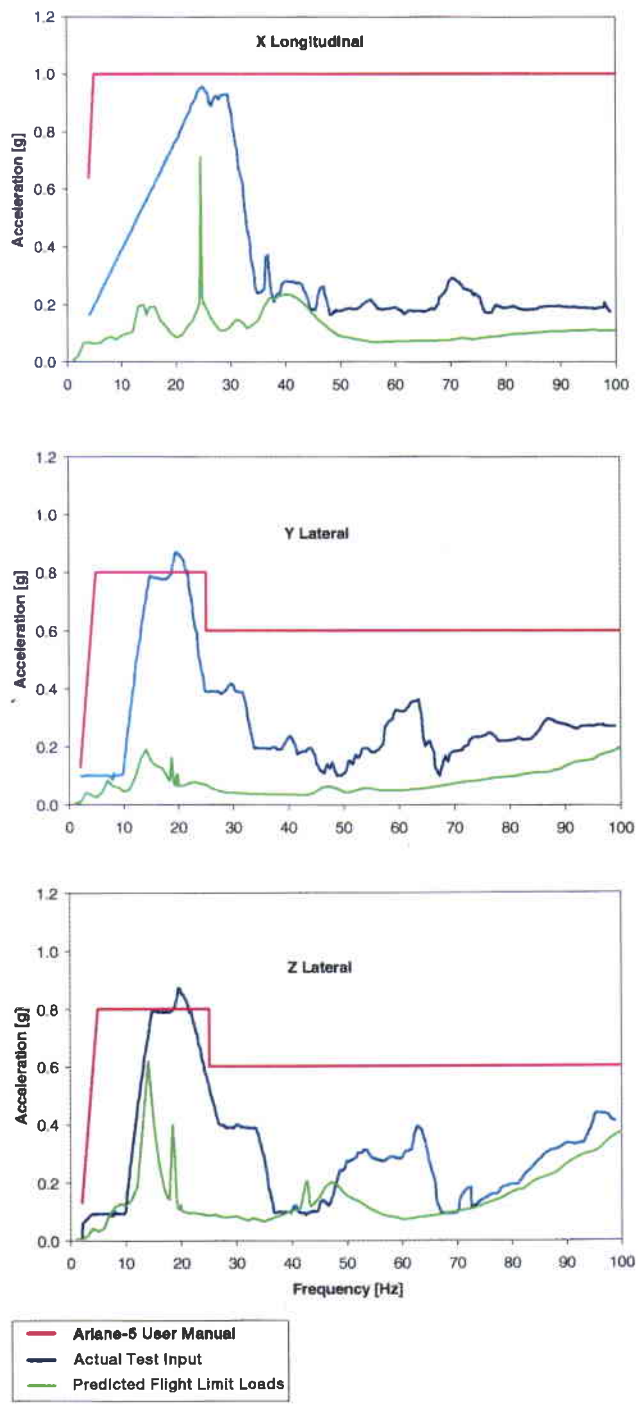


Figure 9. The sine-vibration spectra

Acoustic tests on both the structural and the flight models (Fig. 10) of the satellite were conducted in the Large European Acoustic Facility (LEAF) at ESTEC. The structural-model test had allowed the derivation of random qualification levels for equipment and instruments. The acoustic spectrum required by Arianespace has an overall level of 142 dB. The level for the Envisat acceptance test was 138 dB. These reductions were possible following flight experience with a number of Ariane flights, and changes to the launch pad and fairing.

One issue that caused some difficulty during the development programme was shocks propagating into the spacecraft from the separations of the fairing and of the spacecraft from the launcher. In the event, the launcher authority designed a shock-attenuation device for Envisat and a number of other missions. Also, a piece of pyrotechnic test hardware was specifically designed to produce the specified shocks at the spacecraft interface, rising from 60g at 300 Hz to 2000g at 2500 Hz. Shocks propagating to the lower levels were significantly above design levels for a number of equipment items, but the test was survived without the slightest damage to any spacecraft hardware, and without any change in the status of the relays.

A second issue of concern during the development programme was micro-vibration, with a number of the optical instruments being sensitive to small imported vibrations during the mission. Analysis and some measurements showed that most noise was produced by the AOCS reaction wheels, and by the Stirling-cycle coolers in two of the instruments. Subsequent analysis has shown that the worst-case micro-vibration at the instrument interfaces would cause about a 0.1-micron displacement and a 0.2 microrad rotation. These levels are acceptable by all instruments.

Thermal

The satellite is designed to fly along the direction of the ASAR antenna, with the solar-array end of the spacecraft pointing towards the Sun, which appears to rotate around the spacecraft once per orbit. One orbit takes about 100 min, with about 30 min in eclipse. The other end of the spacecraft points towards deep space and is used to accommodate the infrared instruments, which require a cold environment for their detectors.

Reuse of Spot and ERS heritage technology dictated a flight direction at right angles to the longer dimension of the spacecraft. This implied that instruments on the cold tip (which points towards deep space) had to be specifically designed to fit into the limited surface area. It also implied that the ASAR antenna had to be designed to fold up for launch.

The spacecraft's thermal design is driven by the orbital conditions, and by the need to survive in the Sun-pointing safe mode. The thermal design of the box structure of the basic spacecraft is classically passive. Portions of the box's surface serve as radiators, whilst the rest is clad in multi-layer insulation. Externally mounted items, especially the instruments, are designed to have as little thermal interchange as possible with the box structure itself. Systems of heaters operated by thermostats protect equipment in safe mode. Specific thermostat-controlled heaters protect the hydrazine system and the batteries. Software-controlled heaters are operating at other times when on-board computers are available to control them. The Instrument Control Unit of each instrument controls the thermal management of that instrument when it is on. A number of optical instruments incorporate heat pipes to transfer heat away from detectors to appropriately positioned radiator plates.

In view of its size, it was impossible to perform a thermal test on the spacecraft as a whole. The flight models of the Service Module and Payload Module were tested separately. Even so, the Payload Module could not be loaded directly into the ESTEC Large Space Simulator, but was separated between levels three and four and the pieces re-mated inside the chamber (Fig 11).

The thermal-balance test on the Service Module was of the classical type, using solar simulation and liquid-nitrogen-cooled shrouds. Performed during December 1996, it validated the performance of the thermal hardware and led to satisfactory correlation of the thermal mathematical models. It also revealed that the RCS heater power was insufficient. The necessary hardware modifications, such as the wiring up of available trim heaters and new additional heater circuits, were therefore incorporated after the test.

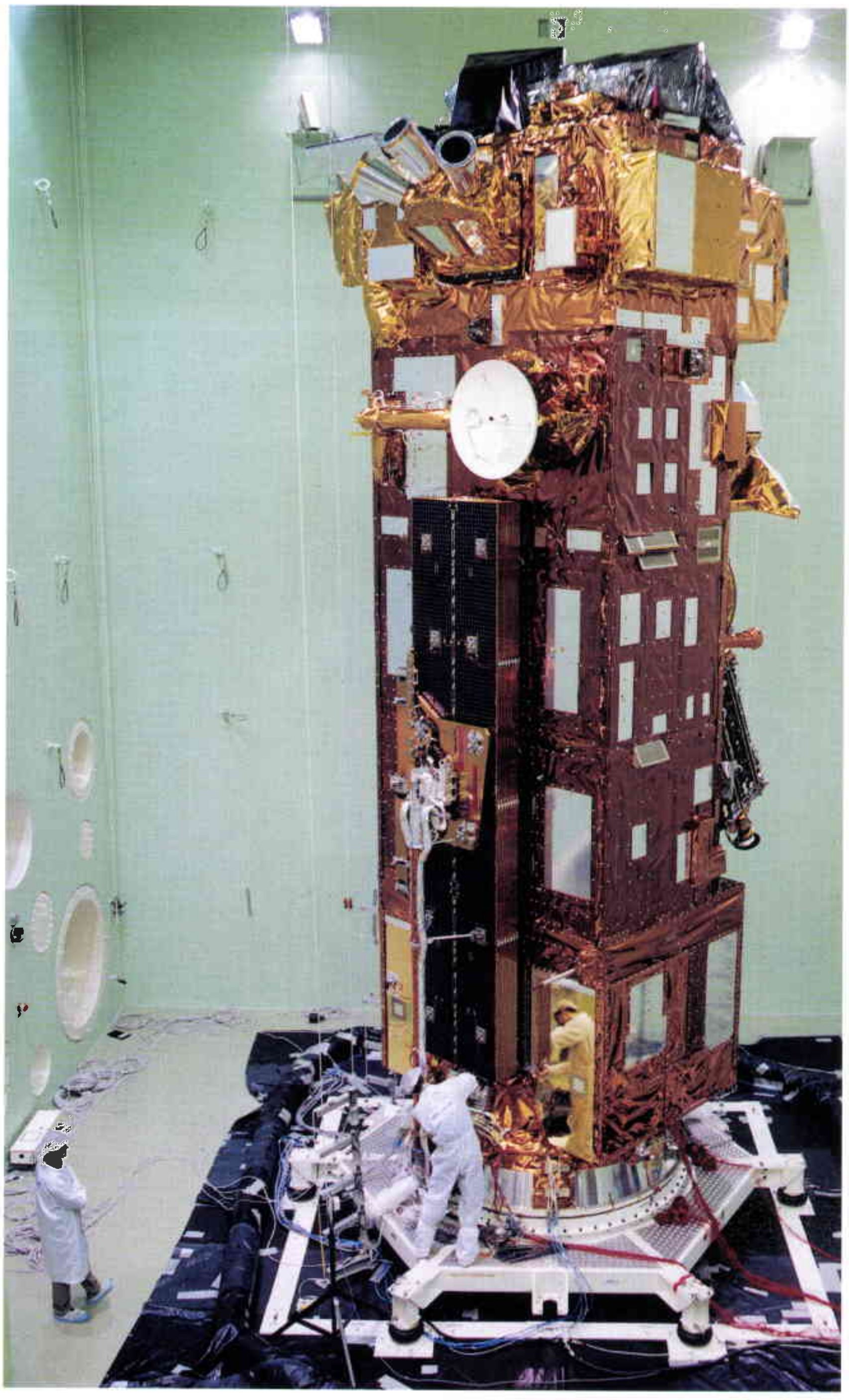


Figure 10. Envisat being installed in the LEAF acoustic facility at ESTEC, with the solar array in the foreground

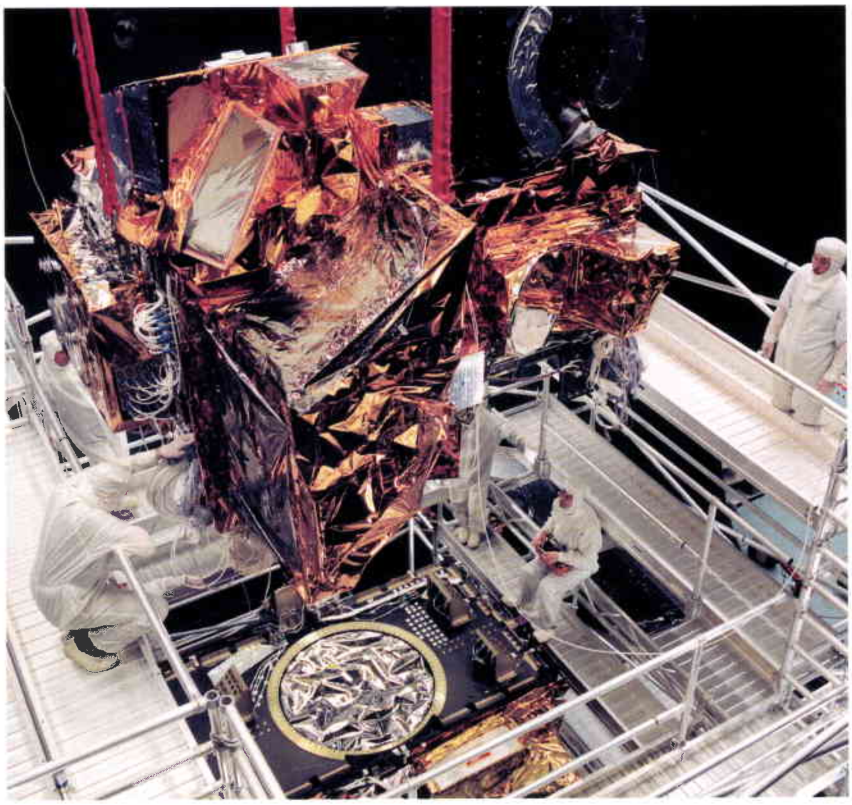


Figure 11. Upper level of the Envisat payload being loaded into the Large Space Simulator (LSS) facility at ESTEC, for mating with the three lower levels

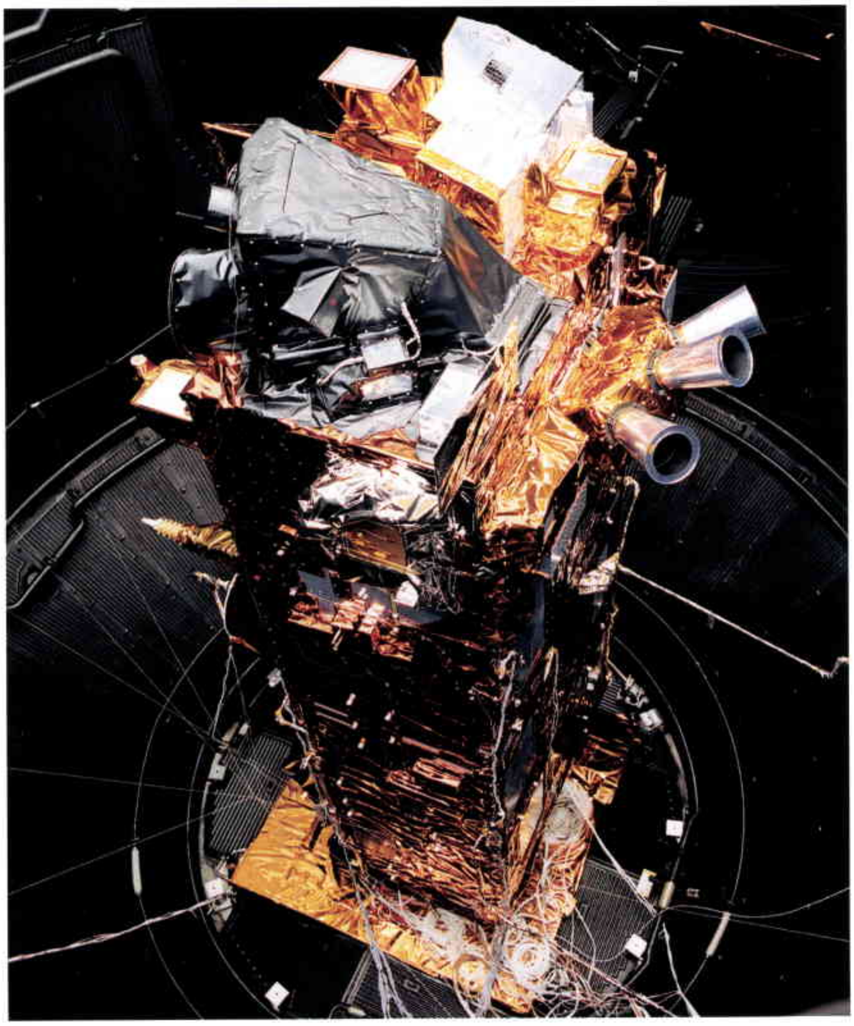


Figure 12. The complete Envisat payload in the LSS at ESTEC

The Payload Module thermal-balance test was performed during August 1999. The physical size of Envisat (Fig. 12) also made it impossible to illuminate it adequately with a simulated Sun. Consequently Sun, Earth and albedo inputs were modelled by the use of elevated shroud temperatures and test heaters. The size of the Payload Module made it necessary to utilise the full facility data-handling capacity of more than 800 thermocouple channels.

Thermal testing of the flight payload showed a poor design of the vent holes for the internal compartments. Inappropriate siting of ion gauges also hindered measurements of vacuum. As a consequence, high-voltage equipment could only be switched on safely late during the test, such that the thermal-balance test phases had to be executed without X-and Ka-band operation. Additional test phases characterising the thermal performance of these two subsystems had to be added. After the test, the vent holes were enlarged and a short handbook prepared on the use of ion gauges.

The test verified the performance of the thermal hardware and allowed correlation of the various mathematical models of the Payload Module and instruments. However, it also revealed that the heater power for the RCS thrusters was insufficient for flight and corrective measures have been implemented.

Electrical

The power subsystem uses eight nickel-cadmium batteries, each of 40 Ah, and a solar array delivering more than 6.75 kW at end-of-life. Power is provided to the satellite via unregulated (22 – 37 V) and regulated (50 V) buses. The main power supply to the Payload Module is via four permanent high-power unregulated buses routed directly from the Service Module power source point. The power-bus voltage follows the battery charge/discharge characteristic. A junction and shunt regulation unit (RSJ) acts as the main interface between the solar array and batteries, taking into account varying power demands. A power distribution unit (BD) provides the necessary switching and protection of power buses supplied to the Service Module.

Within the Payload Module, power is distributed via two Payload Power Distribution Units (PPDUs), which are controlled and monitored by the Payload Module Computer. Each unit provides power switching and protection of power feeds. One of the distribution units is dedicated to the instruments, the other to Payload Module equipment. Both distribution units are located as close as possible to the SM/PLM interface in order to minimise power-harness voltage drops. During testing on the flight-model satellite, a design fault was discovered in a PPDU that allowed the unit to be switched off in a configuration in which it could not be switched on again. A design modification was introduced to cure this.

The size and complexity of Envisat has resulted in more than 700 kg of harness being used on-board. It seems that electrical design approaches such as are being applied on large aircraft might become appropriate for this class of spacecraft.

in the ASAR antenna, it was discovered that the receivers were susceptible to RA-2 transmissions. Filters were fitted to the transmit modules for 12 tiles to avoid this. In all other cases, tests conducted at equipment level demonstrated compliance with these levels.

RF compatibility tests on the engineering- and flight-model satellites (Fig. 13) with deployed antennas demonstrated compatibility of the entire operating satellite with the transmitted power levels. These two tests each involved the construction of a large RFC facility covered with RF-absorbent cones within the clean room. The supporting structure was built by Brilliant

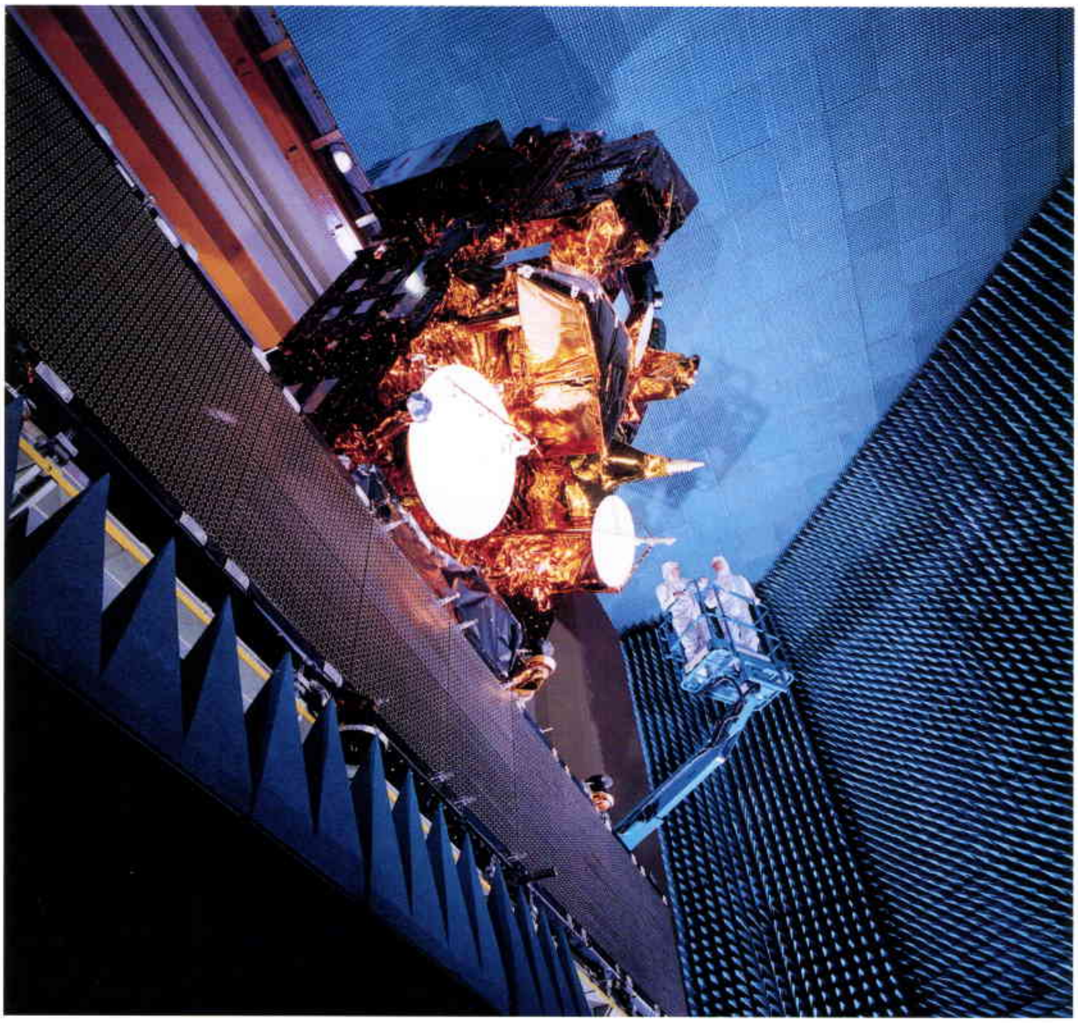


Figure 13. Flight model of Envisat being prepared for RF compatibility testing, with the ASAR antenna at the bottom of the picture

Electromagnetic and radio-frequency compatibility

EMC/RFC aspects of the spacecraft are dominated by the radiated field from the on-board radars, and from the Ka-band transmissions to Artemis. Test requirements include:
- 62 V rms from 2.0 to 2.5 GHz S-band
- 80 V rms from 3.0 to 3.4 GHz RA-2 S-band
- 160 V rms from 5.15 to 5.5 GHz ASAR
- 80 V rms from 13.2 to 13.9 GHz RA-2 Ku-band.

While testing transmit/receive modules for use

Stages, a company better known for its work on outdoor rock concerts, but it was able to work quickly and effectively in parallel with normal testing. In the case of the engineering-model spacecraft, the facility entirely surrounded the spacecraft. The facility for the flight model was simplified so that only a corner and a roof were constructed to avoid reflections of the Earth-facing antenna beams. The two antennas on the rear side were not radiating during this test, having been validated on the engineering-model satellite.

These radiated-field requirements were supplemented by the usual requirements for compatibility with the launcher. One late demand from the launcher authority originated from a new military radar protecting the launch site itself, but it has also been possible to show that it will not affect Envisat.

Low-frequency conducted interference is dominated by power-bus ripple originating from the on-board Stirling-Cycle coolers, and from the pulsed power demand of the ASAR. Tests at the equipment, Service Module and satellite levels have demonstrated self-compatibility of the satellite in the presence of these signals with a margin of 6 dB.

The satellite has been successfully designed and tested for avoidance of, and immunity to electrostatic discharges. All conductive elements of the structure, including the solar array, CFRP and aluminium panels, thermal blankets and thermal finishes, are electrically bonded together to form an effective equipotential conductive surface, thereby avoiding differential electrostatic charge build-up. All panel surfaces and cable harnesses have also been designed to form a Faraday cage providing electromagnetic shielding.

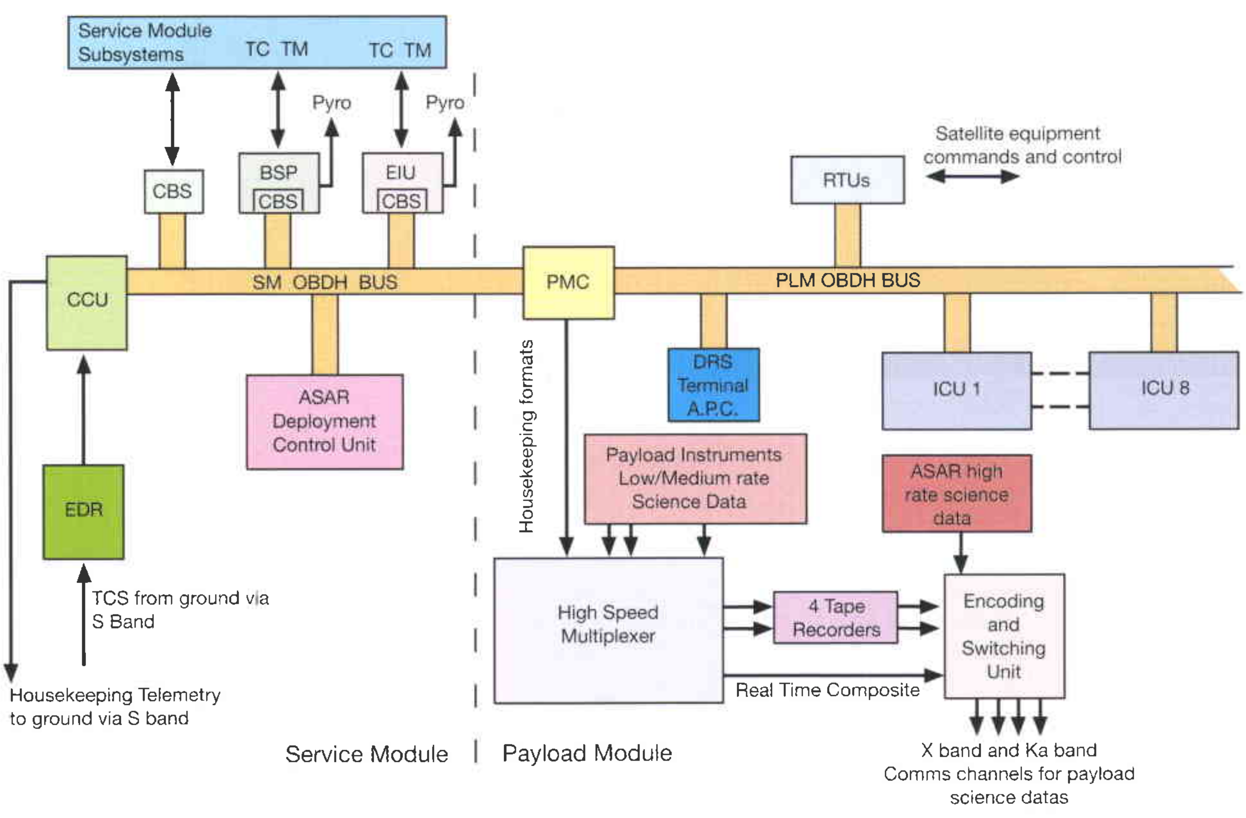
Measurement data handling

This function is responsible for the acquisition, formatting, recording, and communication to the Payload Data Ground Segment of measurement data generated by the Envisat payload (Fig. 14). The High-Speed Multiplexer (HSM) collects CCSDS Instrument Source Packets (ISPs) generated by the payload instruments (at bit rates up to 22 Mbps in the case of MERIS). It formats and encodes these ISP data into Virtual Channel Data Units that are multiplexed together to produce two types of data frames generating Channel Access Data Units (CADUs). One frame is for recording by one of the two solid-state recorders or by the tape recorder, the other is for real-time generation to the Payload Data Ground Segment.

CADU data streams (either from the dumping of a recorder, or generated by the HSM in real time), are collected by the Encoding and Switching Unit (ESU), which routes each of the different CADU data streams to either the X-band or the Ka-band communication subsystem. The ESU also collects the two 50 Mbps data streams from the ASAR payload instrument (this high data rate results from the operation of ASAR in Image mode), and routes them either directly to the communication systems or to one of the two solid-state recorders for later dumping.

The Kiruna X-band ground station provides only about 10 minutes of satellite visibility per orbit. The add-on capability of data relay via Artemis provides an additional 20 minutes of visibility per orbit. Payload data must be

Figure 14. Block diagram of Envisat's On-board Data-Handling (OBDH) System



delivered not later than 3 h after data generation. To meet these constraints, the Payload Module carries two Solid-State Recorders (SSRs), each providing a dynamic RAM capacity of 70 Gbit. These two SSRs allow independent recording (4.6 Mbps) and dumping (50 Mbps) of the Envisat low-bit-rate composite, of the ASAR high-bit-rate data (100 Mbps record and dump), and of the MERIS full-resolution data (22 Mbps record and 50 Mbps dump). Initially, the Payload Module embarked four tape recorders. These units proved to be so questionable that the Agency and its Prime Contractor decided to procure two SSRs. A single tape-recorder unit has, however, been retained on-board as a additional spare capability to record and to dump the low-bit-rate composite.

Envisat is equipped with two distinct communication subsystems accommodated within the Payload Equipment Bay (Table 6). The X-band communication subsystem has three communication channels operable independently and, if need be, simultaneously. Each channel is equipped with a Quadrature Phase-Shift Keying (QPSK) modulator and a Travelling-Wave-Tube Amplifier (TWTA) and, after band-pass filtering, the modulated signals are added through a wave-guide output multiplexer. The resulting composite spectrum is radiated to the Payload Data Ground Segment via a shaped-reflector antenna. The three frequency carriers used by this subsystem are 8.1, 8.2, and 8.3 GHz.

The Ka-band assembly (Fig. 15) is also composed of a three-channel communication subsystem. The assembly uses a 2 m deployable mast located on the opposite side of the satellite to the Earth. The mast is equipped with an azimuth and elevation pointing mechanism, which steers a 90 cm-diameter Cassegrain antenna pointed to the Artemis satellite. Pointing commands are generated by an Antenna Pointing Controller, which is accommodated together with the RF part of the assembly within the Payload Equipment Bay. The subsystem carrier frequencies are 26.85, 27.10 and 27.35 GHz. The system operates in open loop, which means that the Artemis Ka-band transponder will track Envisat using its telemetry, without the need for an extra tracking beacon or tracking receiver.

Table 6. Link budgets

Ground Station Antenna: 32 dB/K G/T	**X-band**
100 Mbps (QPSK)	3.6 dB
50 Mbps (BPSK)	5.7 dB
Ground Station Antenna: 37.2 dB/K G/T	**Ka-band**
100 Mbps (QPSK)	1.64 dB
50 Mbps (BPSK)	4.64 dB

The satellite command and control system
This system is organised around two On-Board Data Handling (OBDH) systems (Fig. 16), a master Service Module data-handling system, and a Payload Module data-handling system slaved to the SM OBDH bus. Each module has a dedicated computer to which equipment items are connected through OBDH digital serial data busses.

Service Module command and control
The SM data-handling subsystem performs the processing and sorage of housekeeping data, the management of telecommand and housekeeping telemetry (at the interface with the S-band ground stations), the data-bus control, the satellite alarms management, and the clock generation to all OBDH peripherals, including the Payload Module.

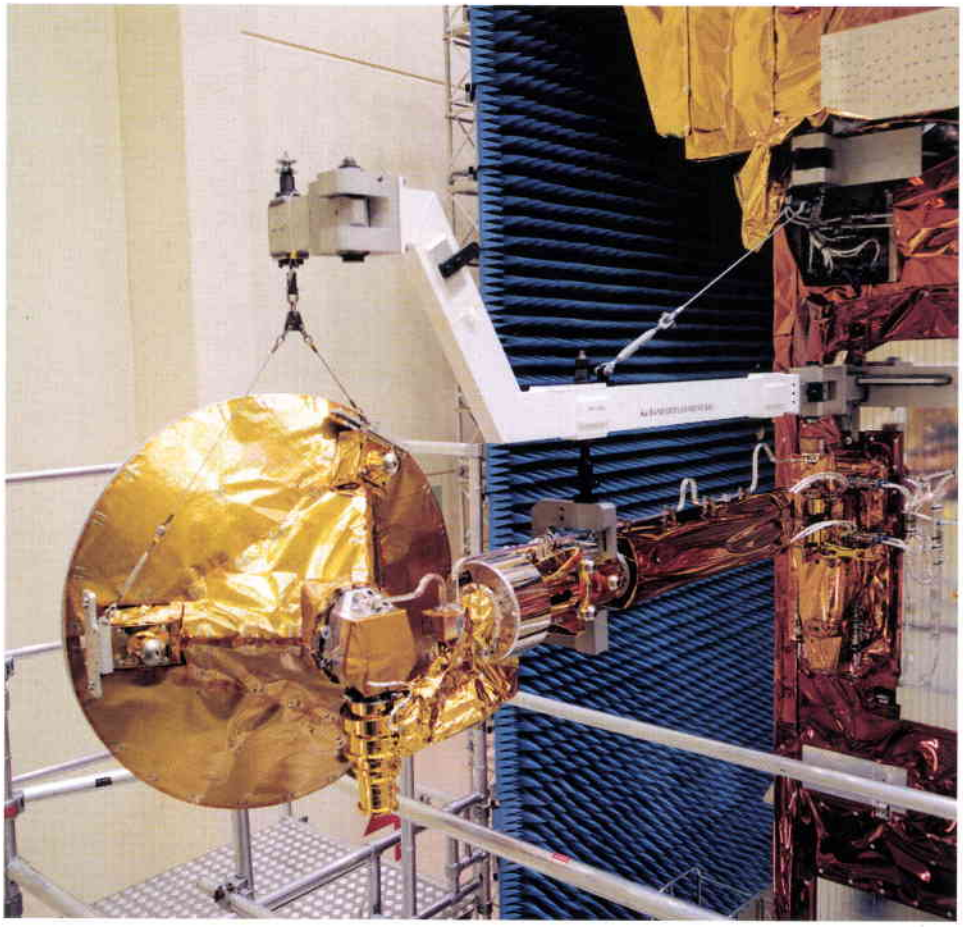


Figure 15. The Ka-band antenna undergoing deployment testing

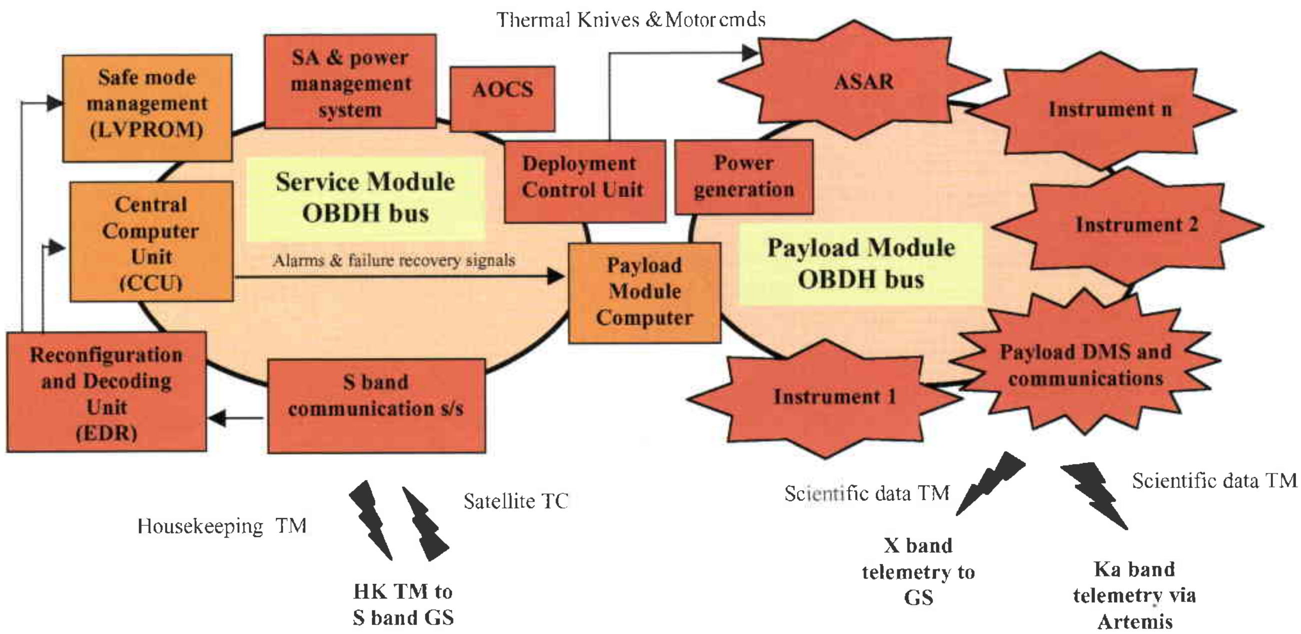


Figure 16. The Envisat satellite command and control concept

It is based on a Central Communication Unit (CCU), which handles the exchange of information between the ground and the SM equipment via the OBDH data bus. It contains an ultrastable oscillator, from which all satellite timing is generated. The CCU communicates through the SM OBDH bus with the Payload Management Computer located within the PLM. The CCU also serves as the main computer for the Attitude and Orbit Control Subsystem (AOCS). Dedicated control algorithms and monitoring functions are implemented into the CCU software.

The Decoding and Reconfiguration Equipment is responsible for receipt of the telecommands generated by the ground segment, and their decoding. This unit also acts as a watchdog with respect to the CCU and can command satellite switch-over to a safe mode in the case of a major CCU anomaly. In such a case, command and control of the satellite's main survival functions relies on software contained in a PROM

The S-band communication assembly provides a bi-directional telemetry and telecommand link with the ground and is used for overall satellite commanding, monitoring and control. It provides a 2000 bps forward and 4096 bps return S-band link to ground, via two S-band antennas operating with cardioid radiation patterns and opposite circular polarisations. Omni-directionality of the link allows communication in any non-nominal attitude. The antennas are connected via a passive hybrid to two S-band transponder systems. Unlike the Spot and ERS transponders, an internal real-time processor pilots the transponder on Envisat. The mission-critical software in this processor was subjected to independent software validation prior to its acceptance. The S-band transponder modulates housekeeping telemetry, demodulates telecommands, and supports ranging and range rating by the terrestrial command and control ground stations.

The SM housekeeping system comprises two units. The housekeeping and pyrotechnic unit (BSP) monitors temperatures and issues thermal-heater and pyrotechnic-firing commands. The Electrical Integration Unit (EIU) arms and powers the thermal knives and motors used to release and to deploy the solar array, monitors its deployment, and enables retraction if required.

The problems experienced during the development and validation of the SM command and control system have been limited because of the experience acquired with this bus for previous missions such as Spot-4 and Helios-1. One exception has been the inheritance of the dual-mode transponder design from Columbus serviceable missions. Because of its mission-criticality for Envisat, this subsystem had to be carefully analysed. Its software was simplified and modified to increase its reliability. To avoid permanent uplink loss due to simultaneous latch-up of both DMTs, the CCU will automatically reset the DMTs if it has not received a valid telecommand within the last 24 h.

Payload Module command and control
The Payload Module avionics is decoupled from the Service Module. Its provides its own power distribution, operates its own OBDH bus, and is controlled by a specific Payload Module Computer (PMC), which performs

tasks including scheduling of the commanded mission, monitoring of the Payload Module systems (Payload Equipment Bay avionics, and payload instruments).

The PMC operates as the payload-instrument master controller. It communicates with the SM via the SM OBDH bus, and commands and controls all the Payload Module equipment and instruments via a separate Payload Module OBDH bus. It also routes housekeeping telemetry back to the PMC for transmission to the SM.

The PMC manages two types of macro-commands; immediate macro-commands, for example an immediate request of a special housekeeping telemetry format during visibility over a ground station, or time-tagged commands destined for PEB subsystems or payload instruments. Mission-planning commands aimed at performing autonomous round-the clock operations without ground intervention are stored as a queue of time-tagged commands.

The PMC gathers and formats PLM subsystem and payload-instrument housekeeping telemetry, which will be merged by the SM CCU with SM housekeeping telemetry prior to downlinking. The PMC transmits to the PEB subsystems and to the payload instrument ICUs, time-synchronisation signals derived from the pulses generated by the SM. This time-synchronisation function allows correlation of the onboard time-of-occurrence of specific events with the UTC time used on the ground.

The PMC also packetises the overall satellite housekeeping telemetry generated by the SM into a stream of ancillary source packets. These ancillary data contain in particular the spacecraft's orbital position parameters with respect to the satellite onboard time. They are used by some instruments to schedule specific activities (e.g. Sun or Moon occultation activities for SCIAMACHY). These ancillary data are also routed to the High-Speed Multiplexer, which allows the ground segment to receive the satellite housekeeping telemetry generated during non-visibility periods.

Instrument Control Units (ICUs) are responsible for the instrument command and control functions, ranging from the management of telemetry/telecommand flows between the PLM OBDH and the payload instrument units (MWR, DORIS), to the management of instrument internal data buses and of communication with secondary scientific processors connected to them (MERIS, RA-2, ASAR). Each payload instrument is equipped with an ICU, as is the Ka-band Antenna Pointing Controller.

Satellite Attitude and Orbit Control System

The AOCS provides three-axis stabilisation of the satellite body, which remains fixed in the local orbital reference frame. It ensures acceptable pointing and pointing-stability performance for the payload instruments and sensors (Table 7).

In nominal operational modes, the CCU software processes all AOCS signals received from the sensors and controls the AOCS modes. Figure 17 shows the satellite AOCS mode transition diagram. The sensors are:

- A set of four independent two-axis gyroscopes: two are used for nominal operations, with the other two remaining in cold backup.
- Two Digital Earth Sensors (DES): one is used for nominal operations, while the other is kept in cold redundancy.
- Two Digital Sun Sensors (DSS): one is used for nominal operations, while the other is kept in cold redundancy. DSS is not used for attitude control in SYSM.
- Three Stellar Star Trackers (SST): any pair used for SYSM, with the third kept in cold redundancy.

In nominal operations, the CCU software computes the attitude and pointing estimation using correction algorithms that are AOCS-mode dependent. It also generates commands to the following AOCS actuators:

- 16 thrusters, 8 allocated to each nominal and redundant actuator chains. They are used for initial attitude control, in- and out-of-plane manoeuvres, and safe mode. The backup thrusters are kept in cold redundancy.
- 5 reaction wheels, each with a 40 Nm/s capacity (two wheels on Y- and Z-axis, one wheel on X-axis)

Table 7. Pointing stability performance for the most demanding payload instruments

Time Period (sec)	Budget for Worst Axis (deg)	Requirement for All Axes (deg)
1.6	0.0017	0.0040 (SCIAMACHY)
4.0	0.0036	0.0040 (MIPAS)
75.0	0.0135	0.0150 (MIPAS)
110.0	0.0138	0.0200 (SCIAMACHY)
120.0	0.0143	0.0300 (AATSR)
170.0	0.0139	0.0300 (MERIS)

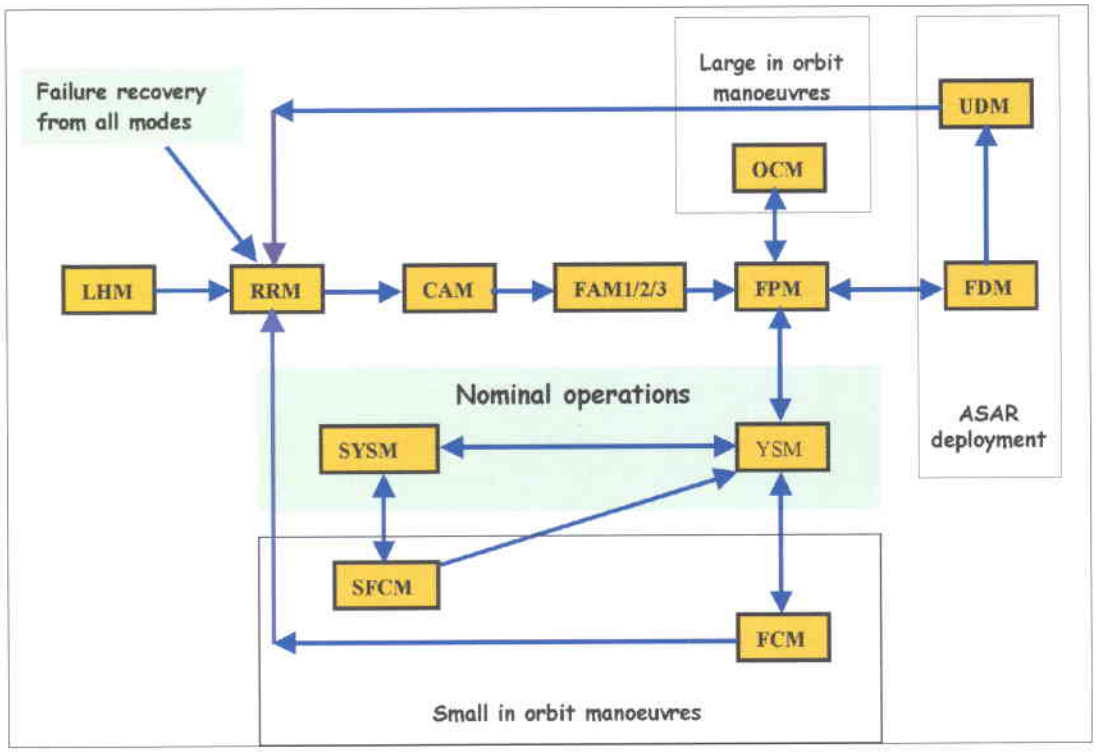


Figure 17. Mode transition diagram for nominal AOCS modes

- 4 magneto-torquers, forming two pairs. They are actuated at the correct satellite orbital phase (depending on their alignment wrt the Earth's gravity field) to control the maximum spin rate of the reaction wheels on the relevant axis.
- 4 tanks containing 300 kg of hydrazine for initial orbit acquisition and orbit-maintenance activities.
- A solar array drive mechanism (MEGS) to control the solar array's rotation (1 rotation per orbit). At a second level, the MEGS is also controlled to compensate for the solar array perturbations due to flexible modes, which are detected by the gyroscopes.

Table 8 provides an overview of the sensors and actuators used for each AOCS mode.

Table 8. Satellite AOCS modes and associated main characteristics

Mode of Operation		Comments	Sensors and Actuators
Operational Mode	YSM or SYSM Geocentric pointing, correction for the local normal pointing, and yaw steering bias	Operational mode with fine satellite pointing	Reaction wheels with magnetic torquers YSM: 1 Digital Earth Sensor, 1 Digital Sun sensor and 2 gyros SYSM: 2 SSTs and 2 gyros
Orbit Control Mode	OCM	Out-of-plane orbit maintenance manoeuvres. $\Delta V > 0.05$ m/s along Y-axis after 90 deg rotation around Z -axis. Payload mission interrupted.	1 Digital Earth sensor 2 gyros 8 thrusters
	FCM or SFCM	In-plane orbit-maintenance manœuvres Mission not interrupted	8 thrusters FCM: 1 Digital Earth sensor, 1 Digital Sun sensor and 2 gyros SFCM: 2 SSTs and 2 gyros
Satellite Safe Mode	SFM	+Z Sun pointing 0.4 deg/s < Satellite rate < 0.65deg/s TM/TC and AOCS control through T4S PROM software.	T4S PROM software-controlled 8 thrusters 2 SAS (+Z and –Z) 2 gyros
Attitude Re-acquisition (exit from safe mode)	RRM->CAM>FAM	Earth re-acquisition by Earth sensors Payload Module put into safe mode	8 thrusters 1 digital Earth sensor 1 digital Sun Sensor 2 gyros

If major anomalies prevent the CCU from performing its nominal tasks (control of the modes above), a specialised Service Module PROM-driven processor (the T4S) can take over AOCS control and keep the satellite in a healthy power and thermal configuration, in so-called 'Satellite Safe Mode' (SFM). The SFM uses attitude information from two specialised Sun-acquisition sensors and rate information from two two-axis gyros. In SFM, the satellite's attitude is controlled by thrusters, the nominal satellite zenith axis is pointed towards the Sun, and a slow angular rate (0.4 – 0.6 deg) is maintained around Z to keep all of the satellite equipment in a safe thermal equilibrium.

The prime satellite AOCS operational mode is stellar yaw-steering, deriving the satellite attitude from the SSTs and the satellite rates from the gyroscopes. Commands are sent to the SST sensors using a ground-based star catalogue tuned to the spectral characteristics of the SST optics. The time of detection of the commanded star, and its position within the SST field of view allow the onboard software to derive an attitude measurement for the satellite. The SYSM software uses SST attitude-measurement data from two of the three SSTs (all accommodated on the Payload Module) along with rate data from two-axis gyroscopes. Within the CCU, these data are combined to derive an estimate of the satellite pointing with respect to the orbital reference frame (close to the most pointing-demanding limb-sounder instruments such as MIPAS), along with the necessary pointing corrections to be applied through commands to the reaction wheels. The generated commands create control torques using the five reaction wheels accommodated along the three satellite axes to keep the satellite pointing as close as possible to the required orbital reference frame, thereby ensuring the required satellite pointing. In addition to attitude-control torques, the magneto-torquers are activated in phase with the satellite position on the orbit to maintain the reaction wheels within operational limits.

In addition to SYSM, there are two other modes (FPM and YSM) that use wheels for fine attitude control. Both of these modes use gyroscopes, Earth sensors and Sun sensors for attitude determination. In the event of complete SST failure, the YSM mode can form a backup operational mode (used nominally on ERS-1 and -2) with degraded pointing and rate performances arising from sensor errors and measurement frequency. Currently, these two modes are only used as transition modes to enter SYSM.

Attitude control using thrusters results in coarse pointing performance. The other satellite modes are used for orbit maintenance or operational transition towards fine-pointing modes. These modes use monopropellant thrusters for attitude control. In these coarse pointing modes, attitude measurement is provided by a Digital Sun Sensor, a Digital Earth Sensor, and two two-axis gyroscopes.

Orbit manoeuvres are required to achieve the correct orbit following separation and to correct the spacecraft altitude (compensation of the air-drag effect) and inclination over the mission's lifetime. Inclination manoeuvres require delta-V firings normal to the orbital plane, which is achieved by rotating the spacecraft by 90 deg, before and after the firing. For protection against mis-pointing, vulnerable instruments are switched to either standby or heater mode during the manoeuvre. Large in-plane manoeuvres (via Orbit Control Mode, OCM) for initial orbit acquisition or repeat-cycle changes are also undertaken by using an OCM sub-mode. Small firings in the plane of the orbit, through the FCM, are used to compensate for air-drag effects. During these FCM manoeuvres, the satellite maintains its nominal attitude and the overall mission is unaffected, although pointing degradation occurs (Table 9).

Table 9. Performance of AOCS non-operational modes

AOCS Non-operational Mode	Axis	Budget (deg)	Requirements (deg)
Fine Acquisition Mode	all	4.90	5.0
Fine Control Mode	X and Y	0.27	0.2
	Z	0.33	0.7
Orbit Control mode	All for in-plane manoeuvres	1.10	2.0
	All for out-of-plane manoeuvres	1.70	2.0
Safe Mode	Z in sunlight	10.50	8.0
	Z in eclipse	17.50	20.0

Acknowledgement
Some of the engineering challenges involved in the long development of Envisat have been described in this article. The development effort has involved literally thousands of people. They should consider themselves thanked here. Obviously they are far too numerous to name. For the authors, it has been an immensely rewarding experience and we look forward to a successful mission.

The Radar Imaging Instrument and Its Applications: ASAR

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Envisat will carry an all-weather, day-and-night high-resolution radar-imaging instrument: the Advanced Synthetic-Aperture Radar (ASAR). ASAR builds on the success of the ERS-1 and ERS-/2 SARs, which have contributed to major scientific achievements and initiated pre-operational and commercial applications of radar data. The ASAR system has therefore been designed to provide continuity with the ERS instrument and to extend the range of measurement capabilities. Three new modes of operation, improved performances and new algorithms allow the generation of novel data products, including near-real-time and off-line precision image products, to be provided to scientific, institutional and commercial users, for land, ocean and ice applications.

ASAR mission objectives

The Envisat mission has both 'global' and 'regional' objectives, with the corresponding need to provide data to both scientific- and application-oriented users on various time scales. Important contributions from the ASAR to the global mission include:

- measuring sea-state conditions at various scales
- mapping ice-sheet characteristics and dynamics
- mapping sea-ice distribution and dynamics
- detecting large-scale vegetation changes, and
- monitoring natural and man-made pollution over the oceans.

ASAR will make a major contribution to the regional mission by providing continuous and reliable data sets for applications such as:

- offshore operations in sea ice
- snow and ice mapping
- coastal protection and pollution monitoring
- ship traffic monitoring
- agriculture and forest monitoring
- soil-moisture monitoring
- geological exploration
- topographic mapping
- predicting, tracking and responding to natural hazards, and
- surface-deformation monitoring.

Some of the regional objectives – sea-ice applications, marine pollution, maritime traffic, hazard monitoring, etc. – require near-real-time data products (within a few hours of sensing) generated on the basis of user requests. Others – such as agriculture, soil moisture, etc. – require fast-turnaround data services (within a few days). The remainder can be satisfied with off-line data delivery. As well as the ASAR products meeting specific operational and commercial requirements, there will be major systematic data-collection programmes to build up archives for scientific research purposes.

Land

As a result of observing the Earth's land surface with the ERS SARs, a large number of land applications have emerged, several of which are based on important developments that have been made in the field of SAR interferometry. SAR data are already being used for agricultural monitoring, forest mapping, geological exploration and flood mapping, while INSAR measurements of topography and small topographic changes are making major contributions to the assessment of environmental risks from earthquakes and land subsidence.

Ocean and ice

The original focus of the ERS missions was ocean and ice monitoring, and there have been an impressive range of scientific investigations in oceanography, polar science, glaciology and climate research, which will continue to be supported by ASAR. These include measurements of ocean-surface features (currents, fronts, eddies, internal waves), directional ocean-wave spectra, sea-floor topography, snow cover and ice-sheet dynamics. Operational systems have been developed for sea-ice mapping, oil-slick monitoring and ship detection.

Instrument operation

Measurement principle

The antenna beam of a side-looking radar is directed perpendicular to the flight path and illuminates a swath parallel to the satellite's ground track. Owing to the motion of the satellite, each target element is illuminated by the beam for a certain period, known as the 'integration time'. As part of the ground processing, the complex echo signals received during this period are added coherently. This process is equivalent to synthetically forming a long antenna - a so-called 'synthetic aperture'. Assuming a constant angular beam width along track or in azimuth over the entire swath, the achievable synthetic aperture increases with the slant range between satellite and target.

The along-track or azimuthal resolution of a side-looking radar is directly proportional to the antenna length and inversely proportional to the target slant range. Hence, the azimuth resolution of a SAR is independent of the target range, and theoretically equals half the physical antenna length. The achieved resolution is the result of a trade-off against other image quality parameters, such as the radiometric resolution.

The across-track or range resolution is a function of the transmitted radar bandwidth. Pulse-compression techniques are used to improve the performance. The fact that the end-to-end system works coherently means that both the amplitude and the phase relationships between the complex transmitted and received signals are maintained throughout the instrument and the processing chain.

Modes of operation

The ASAR instrument is designed to provide a large degree of operational flexibility. Its main instrument parameters can be selected by ground command for each of the five operational modes (Fig. 1):

- The *Image* mode generates high-spatial-resolution data products (30 m for Precision Images), selected out of the total of seven available swaths with a range of incidence angles spanning 15 to 45 deg.
- The *Wave* mode generates 5 km by 5 km vignettes spaced 100 km along-track. The position of the vignette can be selected to alternate between the centres of any two of the seven swaths.
- The *Wide-Swath* and *Global-Monitoring* modes are based on the ScanSAR technique using five sub-swaths, and each generates wide-swath products (400 km) with spatial resolutions of 150 m and 1000 m, respectively.

These four modes may be operated in one of two polarisations, either HH or VV (in this two-

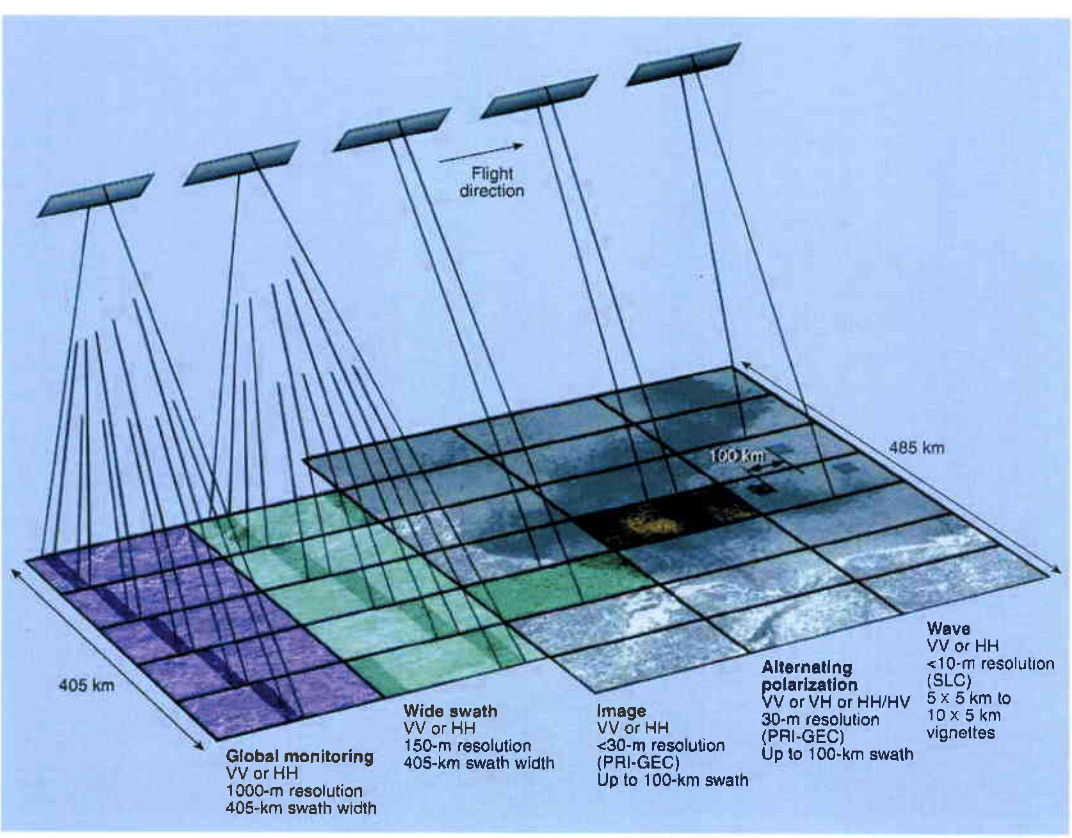

Figure 1. ASAR operating modes

letter code, the first indicates the polarisation of the transmit signal – H for horizontal, V for vertical – and the second indicates the polarisation of the receive signal).

- The *Alternating-Polarisation* mode provides two simultaneous images from the same area in HH and VV polarisations, HH and HV or VV and VH, with the same imaging geometry as in the Image mode and similarly high spatial resolution.

The ASAR instrument

The ASAR instrument consists of two main elements: the Central Electronics Sub-Assembly (CESA) and the Antenna Sub-Assembly (ASA).

Central Electronics Sub-Assembly

The CESA is responsible for generating the transmitted chirp, converting the echo signal into measurement data, as well as controlling and monitoring the whole instrument.

Compared to ERS-1 and ERS-2, which used surface-acoustic-wave devices for analogue chirp generation and on-board range compression, ASAR uses digital technologies for on-board chirp generation and data reduction. A fundamental advantage of this new approach is the inherent flexibility of such a design, which allows chirp versatility in terms of pulse duration and bandwidth, thus accommodating efficiently the various requirements associated with the high number of available operational modes and swaths of the instrument.

At reception, the echo signal is first filtered and down-converted in the RF subsystem, and then demodulated into the in-phase and quadrature components of the carrier. These two signals are then both digitised into 8-bit samples. If required, it is possible to perform digital decimation of the samples, in order to reduce the data stream, such as in Global-Monitoring mode where the transmit bandwidth is low. Following this optional step, a Flexible Block Adaptive Quantiser (FBAQ) compression scheme is applied to the echo samples.

To optimise raw data transfer, the data equipment also contains a 'science memory', where the echo samples are temporarily stored before their transmission to the on-board recorders.

Active phased-array antenna

The ASAR active antenna is a 1.3 m x 10 m phased array (Fig. 2), consisting of five 1.3 m x 2 m panels, which are folded for launch. Each panel is formed by four 0.65 m x 1 m tiles. The Antenna Sub-Assembly is divided into three subsystems: the Antenna Services Sub-System (ASS), the Tile Sub-System (TSS) and the Antenna Power Switching and Monitoring Sub-System (APSM).

The antenna is based on a mechanical structure consisting of five rigid CFRP (Carbon-Fibre-Reinforced Plastic) frames and two (one for the radar signal and one for calibration) RF distribution networks of CFRP wave guides running in parallel along the five panels. In

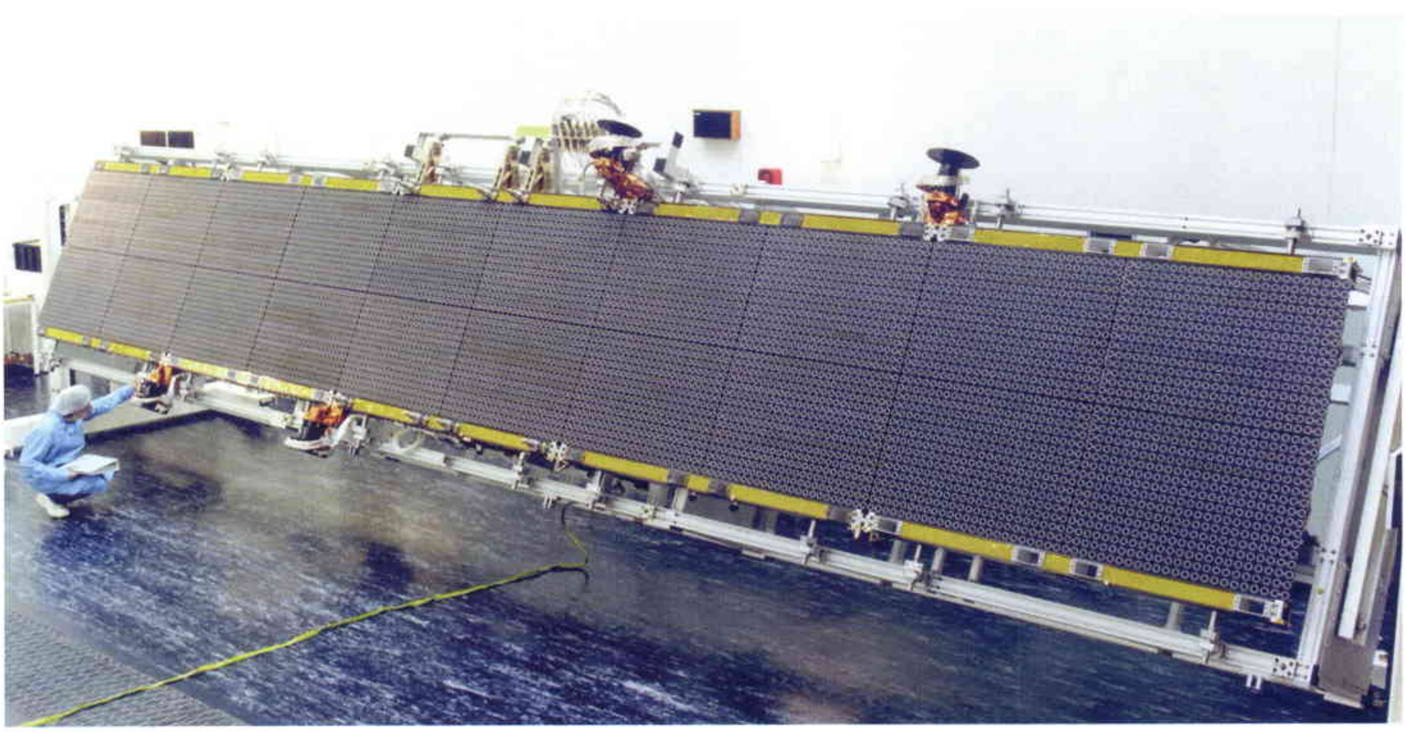

Figure 2. The flight-model ASAR antenna (courtesy of Matra Marconi Space, UK)

launch configuration, the five panels are stowed, folded over the fixed central one, and held in place by eight Hold-Down and Release Mechanisms (HRMs). Each HRM consists of a retractable telescopic tube levered by a secondary mechanism based on non-pyrotechnic technology (kevlar cable and thermal knife). After release, the panels are deployed sequentially around four hinge lines by using stepper motors. Locking is performed by the eight built-in latches to achieve the final antenna planarity of ±4 mm in orbit.

Each of the 20 tiles is a self-contained, fully operating sub-system, which includes four Power Supply Units (PSUs), a Tile Control Interface Unit (TCIU), two micro-strip RF distribution corporate feeds, and 16 sub-arrays of 24 dual-polarised, low-loss, dispersion-free radiating elements. Each sub-array is connected to a transmit/receive (T/R) module with independent connections for the two polarisations. The 16 sub-arrays are mounted together – although thermally and mechanically decoupled – on a single (radiating) panel, which provides structural and thermal integrity to the tile. Pre-flight studies and tests on the engineering model indicate different, but stable temperatures for each operating mode.

Each of the 320 T/R modules consists of two (H- and V-polarised) transmit chains and one common receive chain. For calibration purposes, a coupler (-24 dB) has been implemented at the output of the antenna module (Fig. 3).

For an active antenna, the amplitude and phase characteristics of the T/R modules vary principally as a function of temperature. To handle this, the instrument includes a scheme to compensate for temperature drifts. The temperature of each T/R module is monitored and utilised by the TCIU to compensate for the amplitude and phase variations. This approach provides the antenna with a high degree of stability.

Instrument calibration

The ASAR, unlike the ERS AMI-SAR, is an active antenna, and hence any instabilities in its gain and phase characteristics will distort the elevation beam patterns and may contribute to radiometric errors in the SAR image. For this reason, a sophisticated scheme for radiometric calibration of the ASAR has been selected, composed of three elements: internal calibration, external characterisation and external calibration.

Internal calibration

During normal operation in any of the ASAR measurement modes, a sequence of calibration pulses is interleaved with normal radar pulses. These pulses characterise the active array in both transmit and receive, on a row-by-row basis. Noise measurements are taken during the initial calibration sequences at the beginning of a mode. In the modes that have natural gaps in their imaging sequences (i.e. wide-swath and global-monitoring modes), noise measurements are also made during nominal operation throughout the mode.

External characterisation

The ASAR has a dedicated external-characterisation mode to monitor all those elements that are outside the internal calibration loop, as well as the calibration loop itself. The operation of this mode is planned every 6 months.

External calibration

Acquisitions made over high-precision transponders deployed in the Netherlands and images of the Amazonian rain forest will be used to determine the absolute gain calibration factor and the in-flight elevation antenna patterns. For the ScanSAR modes, the external calibration approach will be similar to that used for the narrow-swath mode, but will also rely on well-characterised distributed targets.

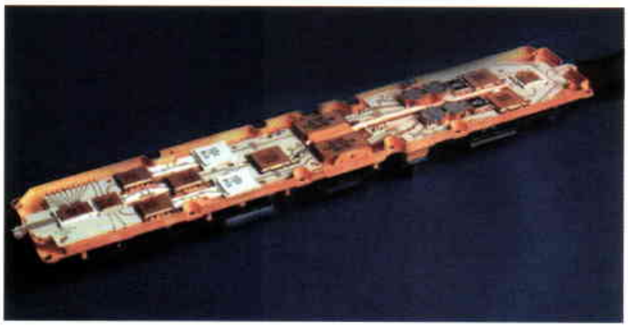

Figure 3. The ASAR transmit/receive module (courtesy of Alcatel, F)

The ASAR ground processor

The development of the ASAR processor has been based on the following concept drivers:

- The need for users to have identical products irrespective of the processing centre.
- The need to broaden the range of products, whilst still ensuring the quality of the ERS SAR high-resolution products.
- The ability to cope with the large amount of products to be generated.
- The ability to generate continuous medium- and low-resolution products along the orbit in near-real-time (strip-line processing, without radiometric or geometric discontinuity).

Following the above concepts, ESA has developed a generic ASAR processor able to handle data from any of the ASAR modes in near-real time and off-line. This ASAR processor will be installed in the ESA Payload Data Handling Stations (Kiruna in Sweden and ESRIN in Italy), in the Low-Rate Archiving Centre in Kiruna, in the Envisat Processing and Archiving Centres (PACs), and in the national stations offering ESA ASAR services. The use of a generic processor will ensure product consistency for the users, regardless of the ESA processing centre selected (same format and processing algorithm) and will simplify product validation and future product upgrade cycles.

One of the key new features of the ASAR processor is its ability to generate medium-resolution (150 m) and low-resolution (1 km) products, with their corresponding browse images, in long strips without geometric or radiometric discontinuity. These strip-line image products represent processed data from an entire acquisition segment of up to 10 min for the Image, Alternating-Polarisation and Wide-Swath modes, and up to a complete orbit for the Global-Monitoring and Wave modes. The product format allows the user to select any scene along-track within the processed segment, without any framing constraints.

To meet the high image-quality requirements, the range-Doppler algorithm is used for the Image mode precision, complex and geo-coded products, for the Alternating-Polarisation mode complex products (with few modifications with respect to the standard range-Doppler algorithm), and for the Wave-mode imagettes. The SPECAN algorithm is used for the non-complex Alternating-Polarisation products and for Wide-Swath and Global-Monitoring modes. Because of its computational efficiency, SPECAN is also used for all medium-resolution products.

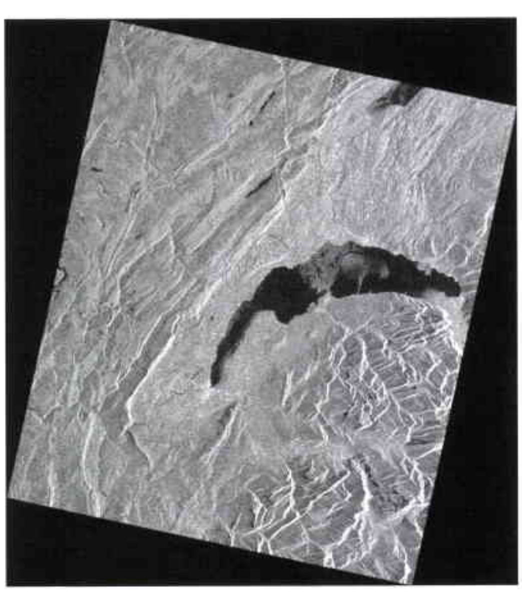

Figure 4. Example of an Image-mode geocoded product showing the Geneva area (from ERS raw data)

Wave-mode imagettes are further processed to the Image cross-spectra and to the Level-2 Wave spectra products via an inversion scheme without the use of any prior information.

Figure 5. Example of an Image-mode medium-resolution product, showing the Ellsworth Highland, Antarctica (from ERS raw data)

The processor computes the replica of the transmitted pulse from the calibration pulse measurements, the row patterns as characterised on the ground, and the external characterisation data. The reconstructed replica tracks variations in the transmit and receive chains and is used to determine the range reference function for compression processing

Noise samples are available in the ASAR source packets at the beginning and end of any acquisition segment and, depending upon the mode, also at regular intervals during the acquisition. They are used to estimate the noise power, which is annotated in the product. No noise subtraction is performed at this stage.

The auxiliary information required by the ASAR processor to perform data decoding, chirp reconstruction and any other correction during the processing (such as the elevation antenna-pattern correction) is provided through auxiliary files. The ASAR auxiliary files are available as standard products, with a certain period of validity (which is annotated in the product) and are generated by dedicated calibration facilities.

The ground processor includes a Doppler Centroid Estimator with a specified accuracy of 50 Hz for the Image and Wave modes, as for ERS, and 25 Hz in the ScanSAR modes in order to limit radiometric errors in azimuth.

The ASAR processor will be used to ensure systematic processing in near-real time of all received high-rate data to generate medium-resolution and browse products. All Wave and Global-Monitoring mode data will also be systematically processed in near-real time.

Furthermore, the ASAR processor will allow high-resolution products to be processed from Image or Alternating-Polarisation acquisitions (Precision Images, Single-Look Complex or Ellipsoid Geo-coded products) in near-real time or off-line, depending on user requests. Figures 4 and 5 show examples of an Ellipsoid Geo-coded Image of Geneva and a Medium-Resolution Image over Ellsworth Highland (Antarctica).

The different products, their coverages and qualities are presented in Table 1.

Applications

Important applications of SAR, like *ocean monitoring and ship routing*, can be satisfied with amplitude images. Figure 6 shows oil spills around oil platforms in the North Sea. The spills

Table 1. ASAR product characteristics

Mode and Product Name	Nominal Resolution (m)	Pixel Spacing (m)	Coverage (km)	Product ENL
IM precision IMP	30 x 30	12.5 x 12.5	56-100 x 100	3.9
IM single look IMS	9 slant x 6	natural	56-100 x 100	1
IM geocoded IMG	30 x 30	12.5 x 12.5	100 x 100	3.9
IM medium resolution IMM	150 x 150	75 x 75	56-100 x 100	40
IM browse IMB	900 x 900	225 x 225	56-100 x 100	80
AP precision APP	30 x 30	12.5 x 12.5	56-100 x 100	1.9
AP single look APS	9 slant x 12	natural	56-100 x 100	1
AP geocoded APG	30 x 30	12.5 x 12.5	100 x 100	1.9
AP medium resolution APM	150 x 150	75 x 75	56-100 x 100	50
AP browse APB	900 x 900	225 x 225	56-100x100	75
WS medium resolution WSM	150 x 150	75 x 75	400 x400	12
WS browse WSB	1800 x 1800	900 x 900	400 x 400	57-62
WV imagette & cross spectra WVI	9 slant x 6	natural	5 x 5 to 10 x 5	1
WV cross spectra WVS	-	-	5 x 5 to 10 x 5	n/a
WV spectra WVW	-	-	5 x 5 to 10 x 5	n/a
GM image GM1	1000 x 1000	500 x 500	400 x 400	12
GM browse GMB	2000 x 2000	1000 x 1000	400 x 400	18-21

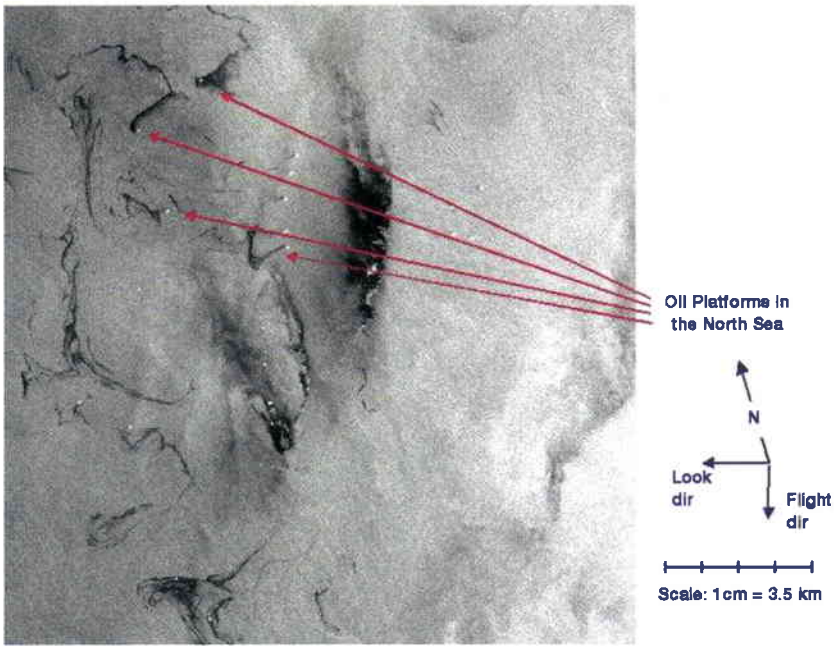

Figure 6. Oil spills detected by ERS-1 (courtesy of the Tromsø Satellite Station, Norway)

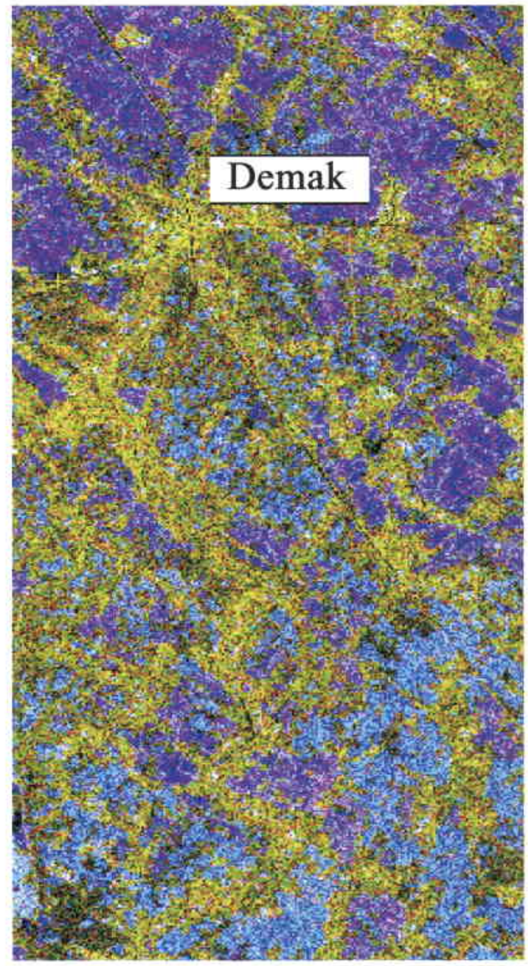

Figure 7. Rice map generated from multi-temporal ERS acquisitions over an area of Java: early rice (magenta), late rice (cyan) and non-rice (yellow) (courtesy of CESBIO, F)

are easily recognised because of their low backscatter, making them appear very dark in the image. Use of lower resolution modes (Wide-Swath and Global-Monitoring modes) provided from ASAR will offer the possibility to monitor larger areas with more frequent revisits.

Another application of high economic importance is sea-ice navigation. Radar-extracted *sea-ice information* can satisfy operational needs for navigation, offshore operations and weather forecasting. Radar images downloaded via the Internet are already being used in real time to organise ice-breaker interventions and to address vessel routes. The variable incidence angle can be used to enhance sea-ice edges. Changing polarisations will allow improved ice-type discrimination and will probably help in the forecasting of leads or ice-pack development.

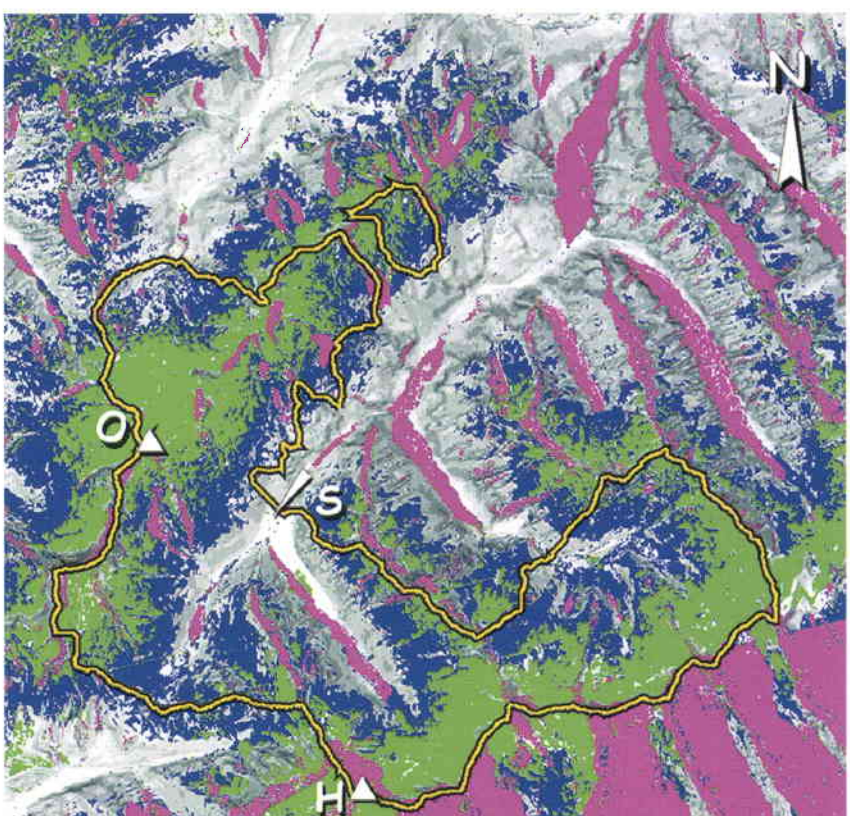

Figure 8. A snow map derived from ERS-2 ascending and descending passes over the Tyrolean Alps

Earth-surface classification is another important SAR application. Most agricultural crops, for example, show a very pronounced change in backscatter as a function of the plant's development. Figure 7 shows a colour-composite generated from multi-temporal ERS-1 SAR acquisitions over Java. Three classes can be easily separated: early rice (magenta), late rice (cyan) and non-rice (yellow). Similar techniques can be used for vegetation, snow and ice monitoring.

The *extent of snow-covered areas* is a key parameter for snow-melt run-off modelling and forecasting. Because SAR sensors provide repeat-pass observations irrespective of cloud cover, they are of particular interest for this application. At C-band, dry snow is transparent and backscatter from rough surfaces below the snow pack dominates. This is why the return signals from dry snow and snow-free areas are very similar. When the snow becomes wet, the

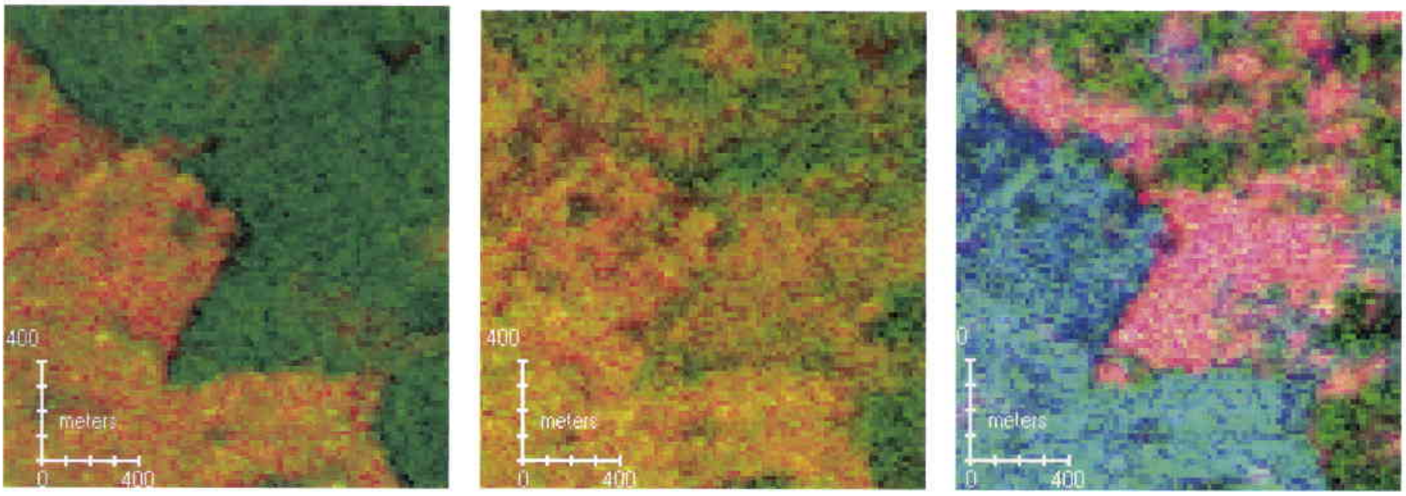

Figure 9. ERS tandem coherence before (left) and after (centre) a storm and the coherence change (right): damaged areas appear in pink tones (courtesy of SERTIT, F)

backscatter decreases significantly. Hence, wet snow can be detected by the temporal backscatter changes when compared to dry snow or snow-free conditions. An example of a snow map derived from ERS-2 ascending and descending passes is shown in Figure 8.

The ASAR's new Alternating-Polarisation mode will increase the number of independent measurements and further enhance the classification capabilities.

Interferometric coherence depends on the stability of the geometric distribution of scatterers, and is therefore very sensitive to surface changes and hence very useful for change detection. The fact that coherence is highly dependent on canopy depth (high for bare soil and low for dense forests) is exploited for vegetation classification.

Storm impacts on forest patches result in an increased level of coherence. By comparing the coherences before and after the storm, the affected areas can easily be identified (Fig. 9). This technique allows *forest-damage assessment* following disastrous storm events.

Floods represent one of the most severe risks for human life and property (Fig. 10). The forecasting, mapping and simulation of floods is therefore essential for the successful planning and operation of civil-protection measures (e.g. for dams, reservoirs) and for early flood warnings (evacuation management).

Hydrological modelling for flood forecasting makes use of interferometrically derived elevation models, soil maps and *soil-moisture* information derived from SAR data. Soil-moisture information is relevant for run-off modelling because it determines the extent of saturation of the watershed, and hence the partitioning of rainfall into surface run-off and infiltration.

The ERS-1/2 missions have successfully demonstrated that the radar cross-section measured over the oceans can be related to wind field. When the ASAR is operated in Wave mode, small areas of the ocean are imaged at regular intervals along the swath and high-resolution complex vignettes are gathered. The retrieval of wind and wave fields is based on dividing the SAR image into a non-linear and a linear part, where the non-linear part is mainly wind-driven and the linear part mainly swell-driven.

The new wind-retrieval methodology is based on using an inter-look processing technique. The time de-correlation measured from the azimuth cut-off of the cross spectrum can be shown to be related to the local wind speed,

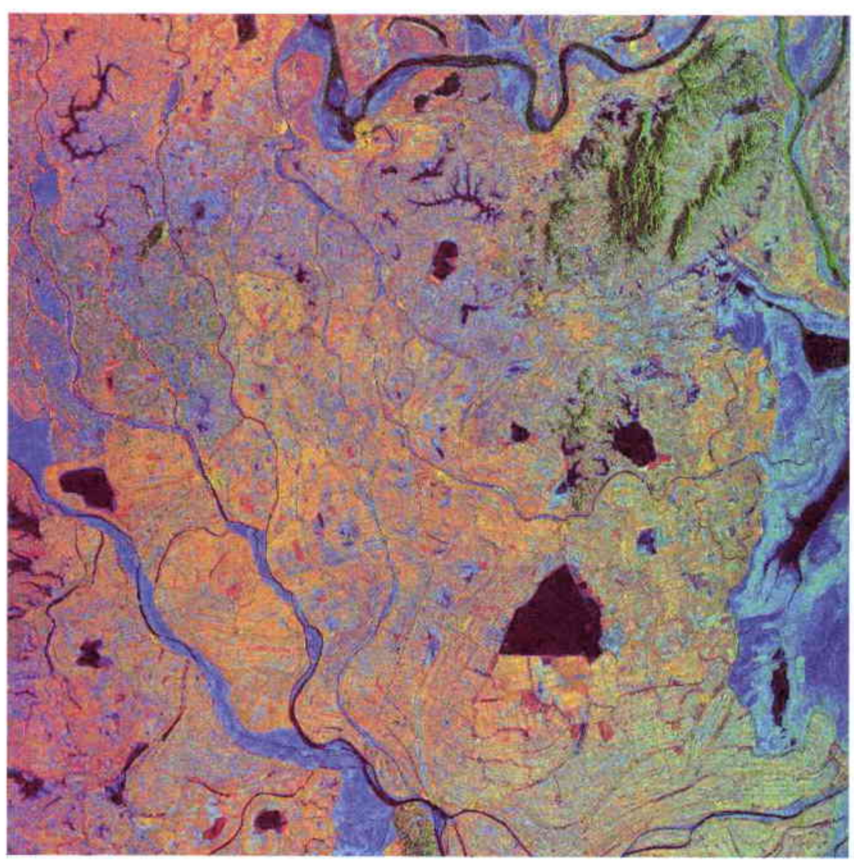

Figure 10. Extent of flooding (blue) around the Yangtze River, highlighted by comparing the coherences of two ERS images from 1995 with two from August 1998
R = coherence in 1998, G = intensity, B = difference in coherence 1998-1995

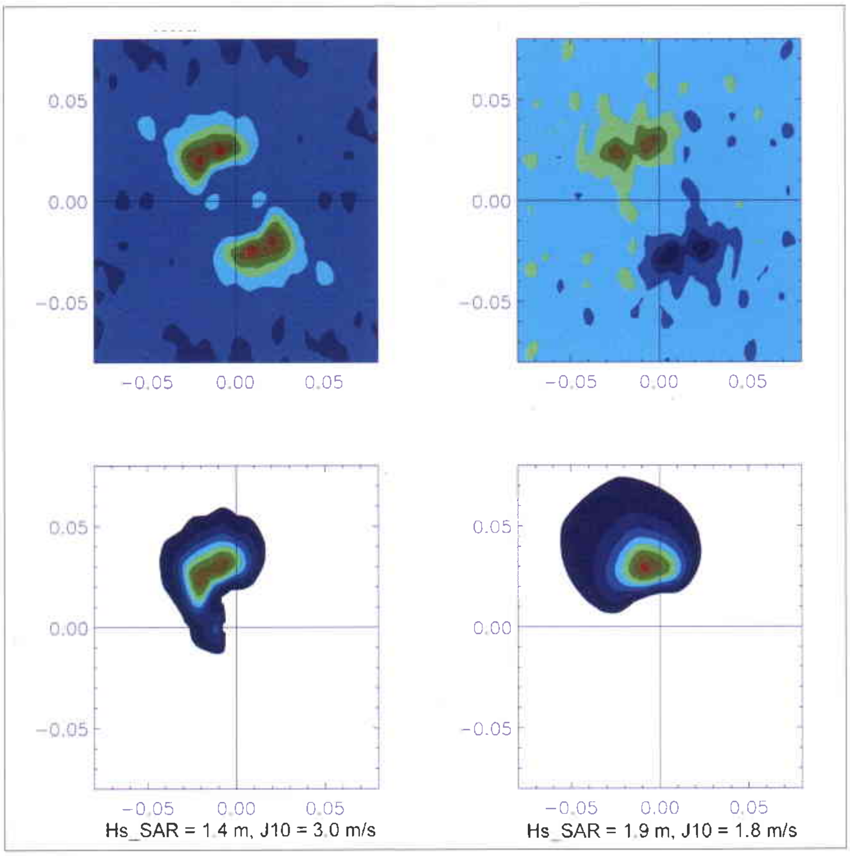

Figure 11. Real (top left) and imaginary (top right) parts of an image cross-spectrum (from ERS data), retrieved wave spectrum (lower left) and modelled spectrum (lower right) for comparison (Hs_SAR = wave height, J10 = wind speed) (courtesy of NORUT, N)

and the phase spectrum of the non-linear part can be used to approximate the wind direction (Fig. 11). These new methodologies will provide meteorological users with wave directional and geophysical parameters and wind parameters, and can also constitute the basis for a future wind-retrieval algorithm tailored to the high-resolution Image-mode data of the ASAR instrument.

Interferometry represents one of the most innovative applications of SAR, and ERS-1 and ERS-2 have made a crucial contribution to the demonstration of this technique. The ERS tandem dataset covers most of the Earth's land and ice surfaces. Digital Elevation Models (DEMs) can be extracted from the interferometric data with an accuracy of up to 5 m, depending upon the terrain's topography and surface-cover coherence (Fig. 12).

Differential interferometry also allows the quantification of surface dislocation and subsidence due to earthquakes and mining activities on a regional scale and with millimetre accuracy. This highly sensitive technique requires acquisitions before and after the surface deformation, and a third image to obtain a reference DEM (existing highly accurate topographic data may also be used).

Figure 12. High-precision Digital Elevation Model of Bachu (China), derived from ERS tandem data (courtesy of DLR, D)

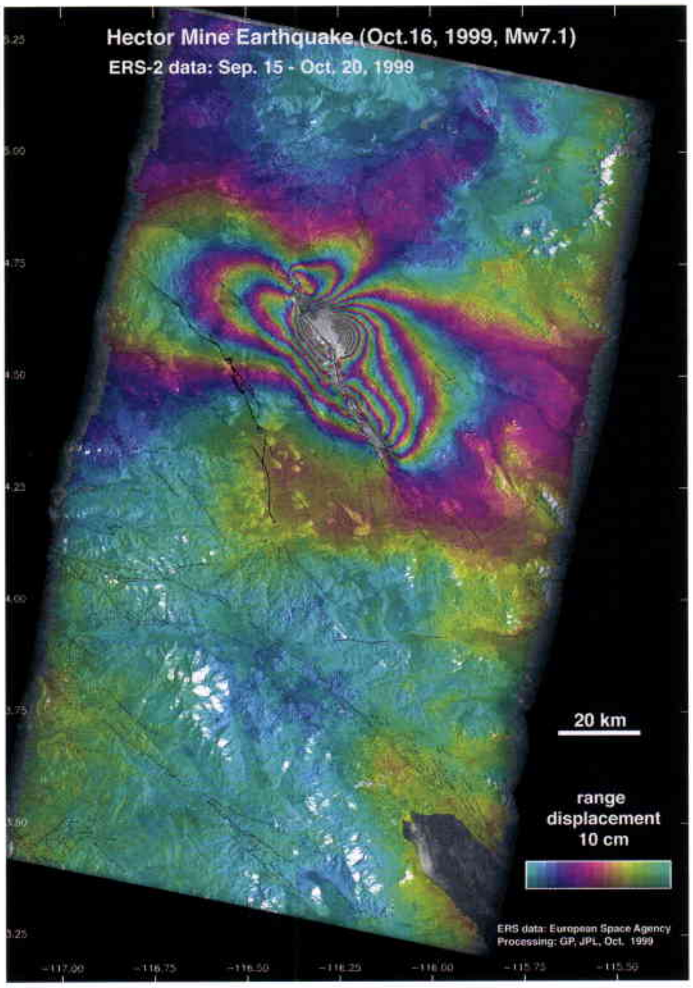

Figure 13. Interferometric map of the Hector Mine earthquake (1999) area in California showing the ground displacement along the radar line of sight. One full colour cycle represents 10 cm of range displacement (courtesy of JPL, USA)

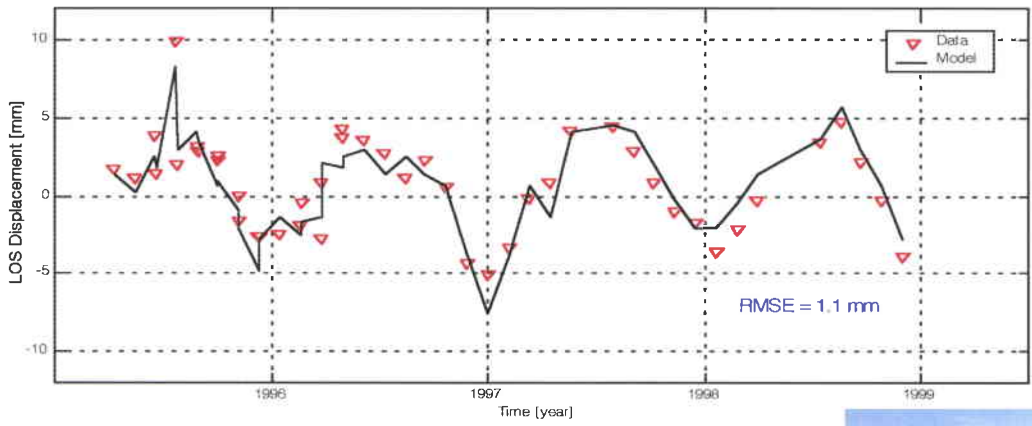

Figure 14. Measured line-of-sight displacement of the La Vilette Science Museum in Paris, compared to the modelled displacement due to temperature variations (courtesy of Politecnico di Milano, I)

This technique has also been applied to the monitoring of glacier movements and to the estimation of the ice flow rates.

Figure 13 is an interferometric map of the Hector Mine earthquake area in California in 1999, showing the ground displacement along the radar line of sight. One full colour cycle represents 10 cm of range displacement. Dotted lines depict California faults, and the thick, solid lines indicate the Landers surface rupture in 1992. Thin, solid lines within zones of dense fringes are surface breaks inferred from azimuth and range disparities (offsets) between before and after images, and phase discontinuities. Co-seismic motion maps could be useful in the emergency response phase of disaster management in order to locate the areas with greatest potential damage (bigger measured ground deformation).

Almost ten years of ERS data made it possible to develop the so-called 'permanent-scatterer technique', which allows one to monitor any movement of these scatterers over several years. Typical permanent scatterers are buildings or other large man-made structures, which are coherent over very long time periods. Figure 14 shows the measured line-of-sight displacement of a large building (steel construction) in Paris, and in comparison the modelled displacement due to temperature variations. The RMS error is 1.1 mm.

Long-term availability of ASAR data will guarantee further exploitation and development of such applications. Interferometric combinations of the ASAR Image and Wide-Swath modes will allow co-seismic motion retrieval by means of low-resolution interferometry.

Conclusion

The ASAR instrument is characterised by extensive flexibility thanks to its five operational modes, its ability to image in horizontal and vertical polarisations, the wide range of incidence angles covered, and the possibility to shape the antenna beam in both transmit and receive by controlling the amplitudes and phases of each of the 320 transmit/receive modules individually.

In order to achieve the required performance and operational flexibility, a large number of new technologies, processes and components have been qualified.

All acquired data will be processed in the ESA ground segment by a generic processor to ensure product consistency irrespective of the processing centre. A large number of ASAR products will be routinely produced and will be made available to the users. ASAR will therefore be an invaluable tool for Earth observation, capable of supporting the following principal applications:
- agricultural, forest, and soil-moisture monitoring
- detecting land-use changes
- responding to natural hazards
- geological exploration
- topographic mapping
- surface-deformation measurements

This large number of applications qualifies ASAR as a precursor to future Earth Watch missions.

Acknowledgements

Many European industries have participated in the efforts required to develop the largest single instrument (and associated ground-processing chain) ever built in Europe for remote-sensing applications. We must limit ourselves here to mentioning only the major industrial contractors: Astrium-Ltd (Instrument Prime), Alcatel Space Industries (Tile Sub-System), Alenia Aerospazio (CESA) and, for the ASAR Ground Processor, MDA as a sub-contractor of Alcatel Space Industries (PDS Prime Contractor).

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The Optical Imaging Instruments and Their Applications: AATSR and MERIS

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The global mission of AATSR and MERIS will make a major contribution towards our understanding of the role of the oceans and ocean productivity in the climate system and will also enhance our ability to model and forecast change. The availability of these two complementary sensors on the same platform also offers new opportunities for the synergistic use of data in multi-disciplinary oceanographic and climate studies.

MERIS is primarily dedicated to observing oceanic biology and marine water quality through observations of water colour. However, it will also make contributions to atmospheric and land-surface-related studies. Similarly, the main role of AATSR is to provide detailed Sea Surface Temperature maps, and yet it also provides the capability to measure a range of parameters for cloud microphysics, plus surface temperatures and various vegetation indices over land. Data from these instruments are therefore applicable to a wide range of environmental application.

Introduction

The Medium-Resolution Imaging Spectrometer (MERIS) to be launched on-board Envisat will provide a unique European remote-sensing capability for observing oceanic biology and marine water quality through global observations of ocean colour (Fig. 1), and will provide continuity with other ocean-colour sensors such as Sea-WiFS and MODIS. The Advanced Along-Track Scanning Radiometer (AATSR) will provide continuity with similar ATSR instruments flown on ERS-1 and 2, thereby ensuring the production of a near-continuous, 15-year dataset of Sea-Surface Temperatures (SSTs) at an unprecedented accuracy level of 0.3 K or better (Fig. 2).

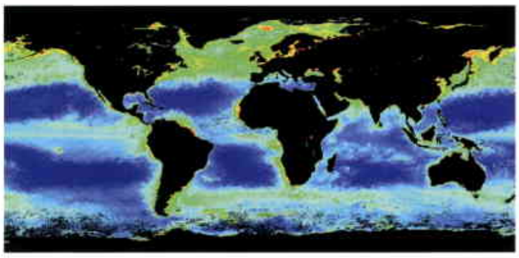

Figure 1. A SeaWiFS image of the global seasonal average of chlorophyll pigment concentration (courtesy of NASA/GSFC and Orbimage)

Biogenic material in our oceans accounts for a large portion of their carbon pick-up, playing a major role in the Earth's carbon cycle and therefore our climate. SST is one of the most stable of several geographical variables which, when determined globally, characterise the state of the Earth's climate system. Phytoplankton concentrations in the oceans, responsible for the latter's primary production, therefore need to be known with a high degree of accuracy for their adequate prediction through modelling. Furthermore, accurate knowledge of marine water constituent concentrations has become mandatory for the assessment of the water quality in marine ecosystems. In parallel, precise measurement of small changes in SST will provide an indication of significant variations in ocean/atmosphere heat-transfer rates and their impact on our physical climate.

AATSR and MERIS are both passive optical imaging instruments measuring radiation reflected and emitted from the Earth's surface. AATSR has four channels in the visible/near-infrared wavelengths and three in the thermal-infrared region (Table 1). MERIS has 15 channels in the visible and near-infrared (Table 2). The overlap between the instrument bands, and the complementary measurements they provide over ocean and land, creates novel opportunities for the synergetic use of data in many fields of study.

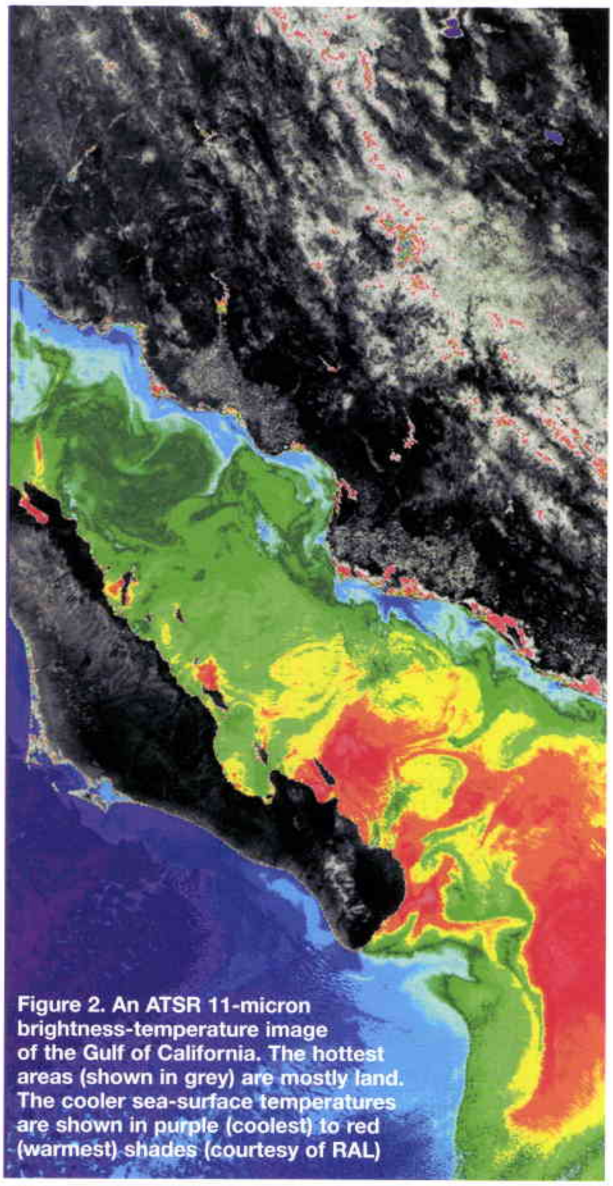

Figure 2. An ATSR 11-micron brightness-temperature image of the Gulf of California. The hottest areas (shown in grey) are mostly land. The cooler sea-surface temperatures are shown in purple (coolest) to red (warmest) shades (courtesy of RAL)

Table 1. AATSR spectral channels

Channel (µm)	Bandwidth (nm)	Primary Application
0.55	20 nm	Chlorophyll
0.66	20 nm	Vegetation Index
0.87	20 nm	Vegetation Index
1.6	0.3 µm	Cloud Clearing
3.7	0.3 µm	SST
11	1.0 µm	SST
12	1.0 µm	SST

Table 2. MERIS spectral channels

Channel (µm)	Bandwidth (nm)	Primary Application
412.5	10	Yellow substance, turbidity
442.5	10	Chlorophyll absorption maximum
490	10	Chlorophyll, other pigments
510	10	Turbidity, suspended sediment, red tides
560	10	Chlorophyll reference, suspended sediment
620	10	Suspended sediment
665	10	Chlorophyll absorption
681.25	7.5	Chlorophyll fluorescence
708.75	10	Atmospheric correction, red edge
753.75	7.5	Oxygen absorption reference
760.625	3.5	Oxygen absorption R-branch
778.75	15	Aerosols, vegetation
865	20	Aerosols correction over ocean
885	10	Water-vapour absorption reference
900	10	Water-vapour absorption, vegetation

The instruments

AATSR

The AATSR (Fig. 3) is the third in a series of similar instruments that use the same innovative features to provide high-accuracy measurements of SST for use in studies of global climate change. The exceptional sensitivity and stability of calibration of these instruments, coupled with the dual-view technique for atmospheric correction, allows measurements of SST to an accuracy of ± 0.3K. These high-quality image data also contribute to a wide range of other scientific studies related to the land surface, atmosphere, clouds, oceans, and the cryosphere.

The first Along-Track Scanning Radiometer (ATSR) was carried on ESA's ERS-1 mission, which operated between July 1991 and March 2000. The second instrument, ATSR-2, followed on ERS-2 in April 1995 and is still operating. The AATSR on Envisat is one of the Announcement of Opportunity (AO) Instruments and has been developed and

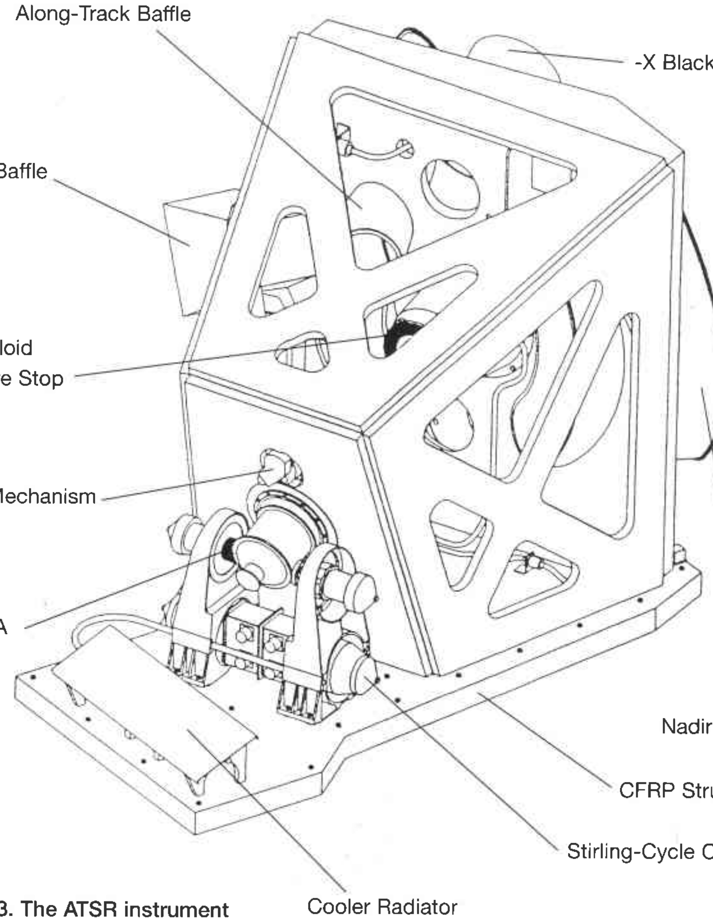

Figure 3. The ATSR instrument

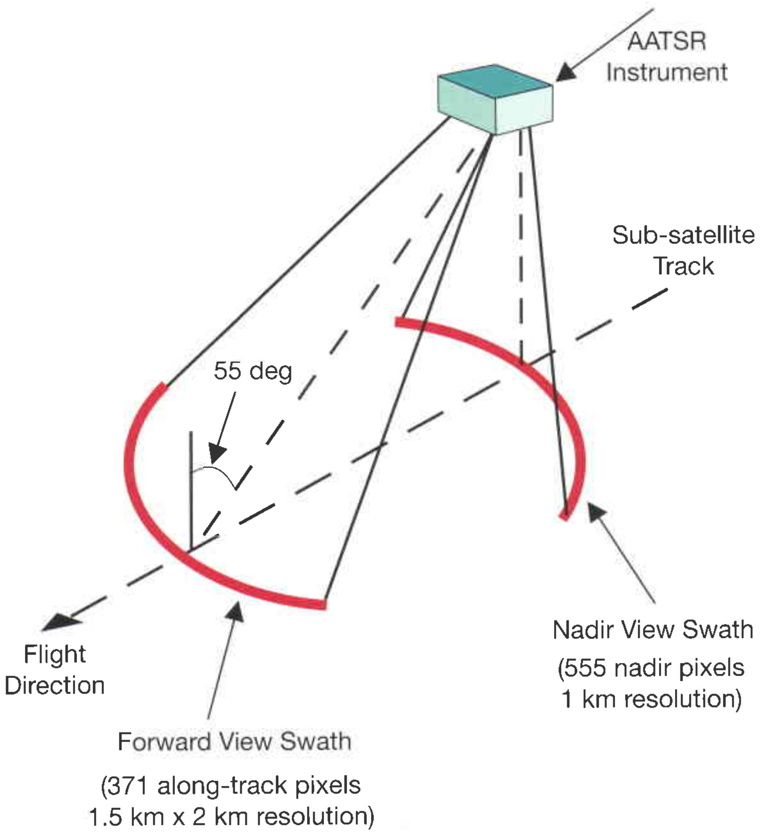

Figure 4. The AATSR viewing geometry (courtesy of RAL)

procured by the UK Department of the Environment, Transport and the Regions (DETR), in partnership with the Australian Department of Industry, Science and Resources (DISR) and the UK Natural Environment Research Council (NERC).

The (A)ATSR instruments are unique in their use of 'along-track scanning' to improve atmospheric correction. Two views of the same point on the Earth's surface are obtained in quick succession at two different angles through the intervening atmosphere. By viewing the same point in this way through different atmospheric paths, it is possible to estimate and correct for the effect of atmospheric absorption. The AATSR viewing geometry is shown in Figure 4. A conical scan projects downwards and ahead in the along-track direction, allowing each point on the Earth's surface to be viewed in turn, first at an angle of 55 deg (the forward view) and then at an angle close to the vertical (the nadir view) as the satellite moves forward. The two curved swaths are approximately 500 km wide, and the nominal size of each pixel within the scan is 1 km.

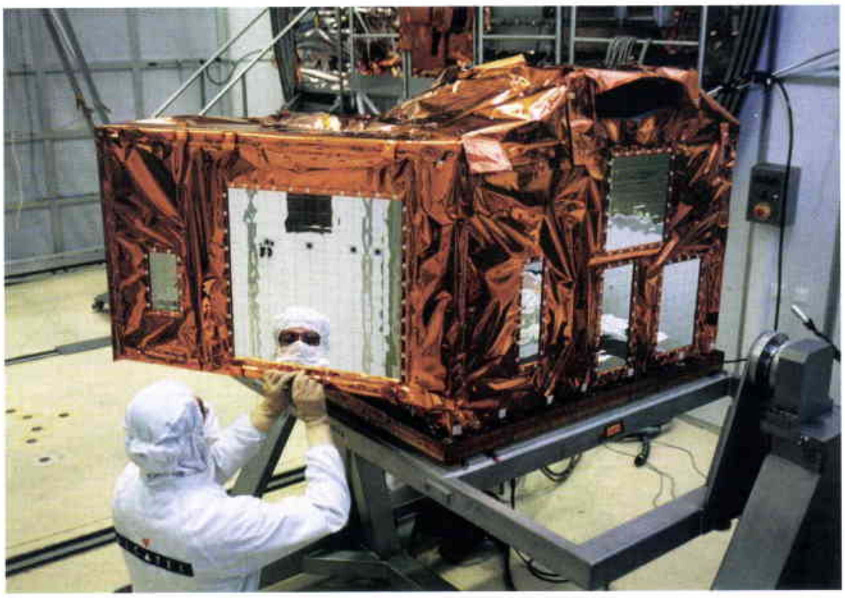

Figure 5. MERIS flight model during integration at Alcatel Space Industries in Cannes (F)

Other key features of the instruments are their low-noise detectors, high-quality calibration and long-term stability. The exceptional sensitivity and stability of calibration is achieved not only by extensive pre-launch calibration, but also through the use of state-of-the-art on-board calibration targets. The instrument carries two black-body targets, which are viewed once per scan. One is maintained at a temperature of about 305 K, just above the maximum temperature expected to be observed over marine scenes. The other is unheated and floats at a temperature close to the ambient temperature of the instrument (~256 K), just below the expected range of marine scene temperatures. The two black bodies therefore span the full expected range of SSTs. As a result, the AATSR can be regarded as a near-ideal radiometer. The use of infrared detectors, cooled to their near-optimal operating temperature by a Stirling-cycle mechanical cooler, further contribute to the overall accuracy of the AATSR's thermal measurements.

Over land, the AATSR visible channels need to cope with all possible normal variations in brightness over the Earth's surface without saturation, whilst maximising the precision of the measurements. To achieve this, the gain and offset of the visible channels is selectable in flight. Calibration of the visible and near-infrared channels is also achieved once per orbit by viewing the Sun through a special Visible Calibration Unit.

MERIS

MERIS is a sensor operated in a push-broom mode and looking in the vertical plane (Fig. 5). It consists of five identical cameras arranged in a fan-shaped configuration yielding a large field of view of 68.5°, or a swath of 1150 km. This modular design has been chosen to ensure high optical image quality over such a large field of view.

MERIS data will be of interest for both global observation and for detailed studies on a regional scale. Full Resolution (FR) data with a 300 m ground resolution at the sub-satellite point is intended for coastal-zone and land monitoring. Reduced Resolution (RR) data at 1200 m, combined with the 1150 km swath that gives global Earth coverage in three days, will be used for large-scale studies.

MERIS operates in 15 spectral bands in the 390–1040 nm range of the visible/near-infrared spectrum. The band positions, bandwidths and gains are programmable in flight. The spectral bandwidths can be adjusted between 1.25 and 30 nm, depending upon the width of the feature to be observed and the amount of energy needed in a band to perform an adequate observation.

The optical signal from the bio-chemical activity in the ocean is strongest in the visible wavelengths. It decreases in the near-infrared, where atmospheric perturbation dominates. MERIS takes advantage of this property by measuring the atmospheric signal at two wavelengths in the infrared (where the ocean is considered to be 'dark') and extrapolating this information to the visible wavelengths; the atmosphere's contribution can then be subtracted from the top-of-atmosphere signal. Outstanding radiometric accuracy is imperative for this correction because, in the visible, 90% of the signal reaching the sensor originates from the atmosphere and only 10% from the ocean. This high accuracy will be achieved by on-board calibration using a Sun-illuminated diffuser plate, in addition to radiometric gain factors, allowing the adequate quantisation of very faint signals from the ocean.

Calibration will be carried out on average once every two weeks, as the spacecraft flies over the south orbital pole and the Sun illuminates the on-board calibration device. MERIS will acquire data whenever illumination conditions are suitable, namely in the day zone of the orbit where the Sun incidence angle is less than 80° at the sub-satellite point.

Instrument inter-calibration
Despite the use of on-board calibration systems, the calibration of each instrument can drift with time and general exposure to the space environment. Both immediate and long-term changes in the performance of the visible channels of both instruments will therefore be monitored as part of the Envisat Calibration and Validation Programme. Since three spectral bands of MERIS coincide with the broader visible AATSR channels, their respective evolutions will be compared. This will not only help to maintain and improve the quality of the calibration of each instrument, but will also open the way for the generation of blended records of the same geophysical parameters logged by the two sensors.

Applications
The primary mission objectives for MERIS are observation of the colour of the open ocean and of marine coastal zones. These objectives have subsequently been extended to the observation of cloud and land properties. Similarly, the AATSR mission objectives have been extended beyond SST retrieval, as its high-quality image data are being used in an increasingly wide range of different EO applications. Table 3 summarises the main MERIS and AATSR products and their respective applications.

Oceans
SST and climate research
The Earth's climate is subject to a great range of variability, both natural and man-induced. Probably the most serious change seen in recent years has been the increase in global temperature, possibly linked to the concentrations of carbon dioxide released into the atmosphere from the burning of fossil fuels. Climate models predict that this increase in carbon dioxide will cause an increase in global temperatures, although the exact scale and pattern of this effect is unclear.

Owing to its relative stability, Sea-Surface Temperature is a particularly important geophysical parameter for the understanding of climate change and the heat exchange between the oceans and the atmosphere. By measuring SST to an overall accuracy of better than 0.3 K (Fig. 6), the AATSR will provide an invaluable dataset on a global scale, which will be accurate enough for detailed climate studies. Measurements from buoys and ships provide similar surface observations, but they can only be sparsely distributed and are prone to measurement inconsistencies; hence the increasing importance of satellite-derived measurements.

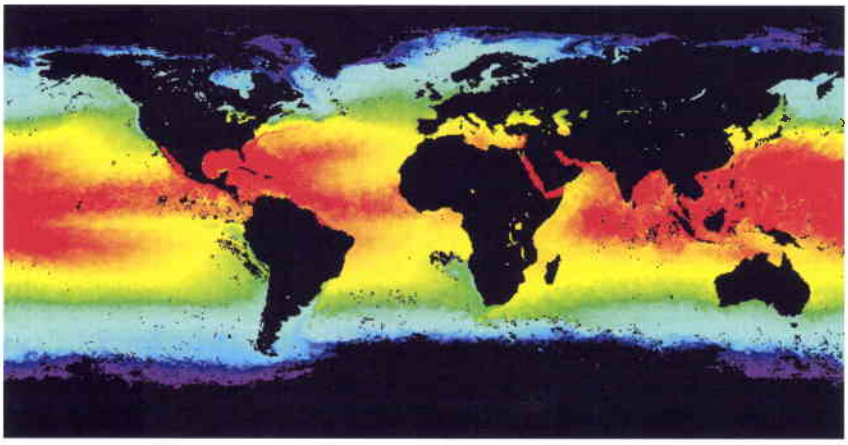
Figure 6. ATSR global SST image from ATSR-2, June 1999 (courtesy of RAL)

Table 3. AATSR and MERIS products and applications

Product	Parameter	Application
	AATSR	
Gridded Brightness Temperature/Reflectance	12, 11 and 3.7 µm TOA BT	Ocean, land, cloud, atmosphere and cryosphere
	0.55, 0.66, 0.87 and 1.6 µm TOA Reflectance	Ocean, land, cloud, atmosphere and cryosphere
Gridded Surface Temperature (1 km)	SST	Ocean and climate research
	NDVI	Vegetation
	LST (currently 11 µm BT)	Land and climate research
	CTT (currently 11 µm BT)	Cloud
	CTH (currently set to zero)	Cloud
Averaged Surface Temperature (10 arcmin, 30 arcmin, 17 km and 50 km cells)	Mean SST	Ocean and climate research
	Mean LST	Land and climate research
	Mean NDVI	Vegetation
	Mean TOA BT 12, 11 and 3.7 µm	Ocean, land, cloud and atmosphere.
	Mean TOA Reflectance 0.55, 0.66, 0.87 and 1.6 µm	Ocean, land, cloud and atmosphere
	Average CTT	
	MERIS	
L1B a) Full Resolution b) Reduced Resolution	Radiance	
Reference L2 a) Full Resolution b) Reduced Resolution	Surface reflectance (land and ocean)	Land, sea and climate research
	Chlorophyll	Carbon cycle, oceanography
	Yellow Substance	Carbon cycle, local applications
	Suspended matter	Carbon cycle, local applications
	Water vapour	Climate research, weather prediction
	Cloud albedo	Climate research
	Cloud optical thickness	Climate research , weather prediction
	Cloud top pressure	Climate research, weather prediction
	MERIS Vegetation Index	Land research

SST data are also useful for studies on a regional scale. For example, SST is a particularly sensitive indicator of El Niño events. This phenomenon occurs when the normal equilibrium of the oceanic and atmospheric conditions throughout the Southern Hemisphere is disturbed by a weakening of the trade winds, causing warming in the tropical Pacific. These El Niño events produce an eastwards flow of warm surface water, a rise in sea level, an interruption in the up-welling of nutrient rich waters, and significant changes in weather throughout the region. Fish die or migrate to higher latitudes, and rainfall patterns change dramatically, with heavy rains and floods on the western coast of South America and droughts in Australia and Southeast Asia. The exact origin of this phenomenon is not well-understood. However, ability to predict the onset and severity of these events can go some way to preparing for and alleviating their effects.

Open ocean

Major uncertainties still remain about the amount of carbon stored in the oceans and the biosphere, and about the fluxes between these reservoirs and the atmosphere. In particular, there is a need for better information on the spatial distribution of biological activity in the upper ocean and its variability over time. Because phytoplankton biomass (Fig. 7) plays a important role in fixing CO_2 in the upper layers of the ocean through photosynthesis, the monitoring of chlorophyll concentration provides the most convenient measurement of its abundance.

The presence of algae, by changing the absorption properties of water, can affect the heating rate of the upper layers of the ocean, modify the depth of the ocean's mixed layer, and influence the seasonal thermocline regime. As a result, ocean colour is rapidly becoming part of dynamical oceanography and it is certainly possible that, within the lifetime of Envisat, the inclusion of chlorophyll data in ocean models will begin to play a role in medium-range weather forecasting.

Over open oceans, MERIS will not only deliver measurements of water-leaving radiance at a range of wavelengths, but will also provide products representing algal pigment concentration, sediment in suspension, dissolved organic matter and radiation available for photo-synthesis. These products, which will be largely compatible with those derived by other sensors (Sea-WiFS, Modis, Polder II, etc.), will provide temporal and spatial continuity with other missions.

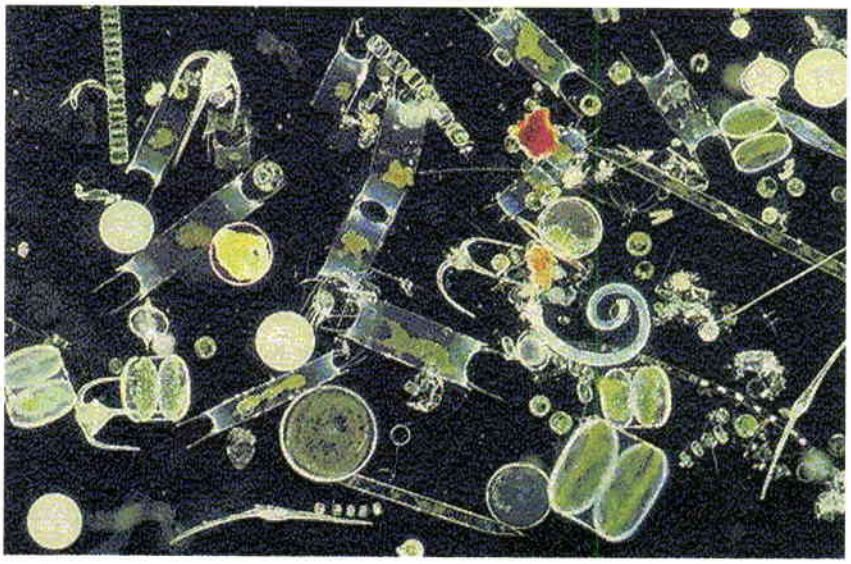

Figure 7. Phytoplankton (courtesy of N. Nichols)

Coastal waters

Coastal regions are some of the most heavily populated in the world and are greatly affected by human activities. Pollutants from rivers and the atmosphere enter the marine ecosystem at this point, disturbing the natural marine productivity. Satellite measurements are ideal for monitoring the environment over such diverse areas.

Once again, the water-leaving radiance measured by MERIS can be used to derive suspended sediment, phytoplankton and dissolved organic-matter concentrations (Fig. 8), which are the major water constituents that control marine and estuarine ecology.

In addition to well-known applications of local, but extremely important, practical interest (such as monitoring the quality of coastal waters, sediment transport, assistance to fishing, and protection of fish and shell farms), MERIS will also provide the first global dataset allowing the exploration of continental-margin carbon fluxes on a global scale.

Synergistic use of ocean data

Envisat will offer data on winds and waves from the Advanced Synthetic Aperture Radar (ASAR), ocean topography from the Radar Altimeter 2 (RA-2), SSTs from AATSR and ocean colour from MERIS, all from the same platform. It will therefore offer unprecedented opportunities for synergistic measurements over the oceans. As an example, data from the first Radar Altimeter have been usefully combined with ATSR-2 SST data to record the rise in both the temperature and height of the sea surface associated with El Niño events. The availability of ocean-colour and SST data co-located both spatially and temporally will also provide a unique dataset for general ocean bio/geophysical characterisation. This is particularly significant, as simultaneous

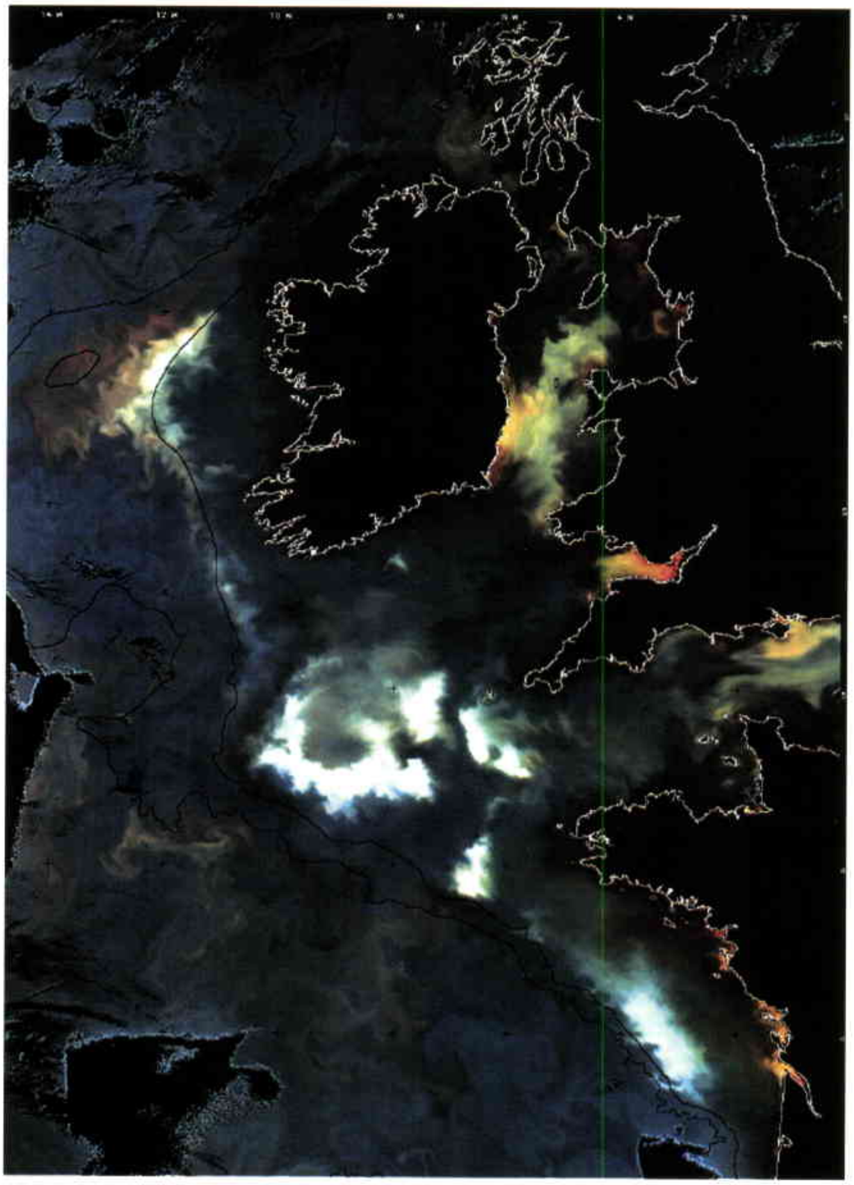

Figure 8. SeaWiFS image of the coastal waters around the United Kingdom on 18 May 1998 (colour composite of 555, 510 and 443 nm bands as red, green and blue, respectively, produced with SeaAPS software). The data were received by the Dundee Satellite Receiving Station (copyright Orbital Imaging Corps and NASA/SeaWiFS)

measurements of comparable spatial resolution at optical and thermal-infrared wavelengths have never previously been available on a routine basis.

Satellite observations can also be combined with a wide range of other data sources. For example, the Clean Seas Project co-ordinated the work of a number of major European research centres in France, Germany, Italy, Spain, Sweden and the United Kingdom in a programme designed to evaluate the contribution that present and future satellite-surveillance systems can make to the monitoring of marine pollution.

The project combined data from a wide range of sources, including low-resolution meteorological satellite data, high-resolution ocean-colour and radar satellite data, and in-situ measurements of meteorological data, to study particular occurrences of algal blooms. The dataset for this project included ATSR imagery in the 0.55 micron channel (Fig. 9) and images from the SeaWiFS instrument, similar to MERIS.

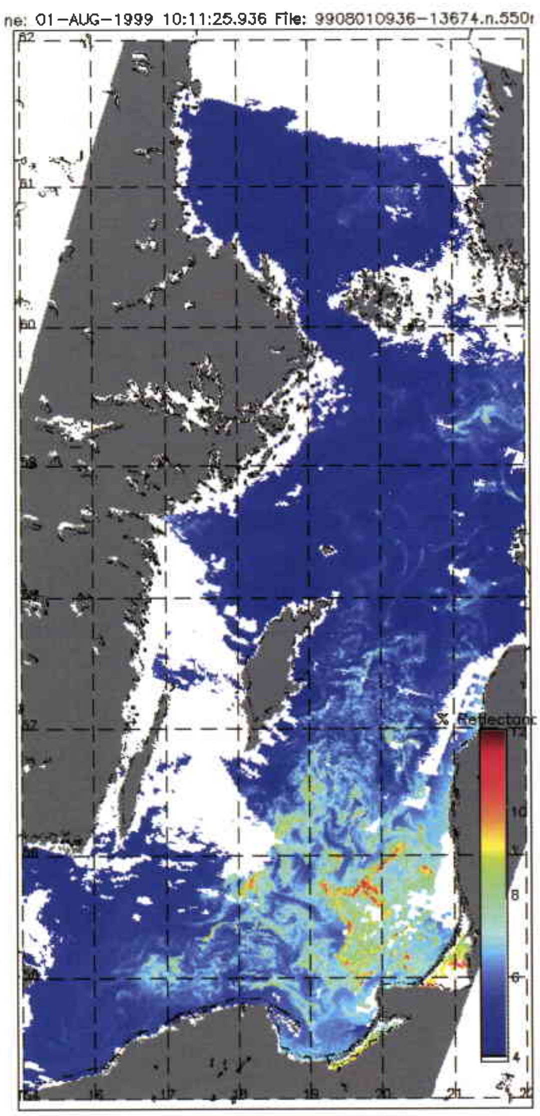

Figure 9. An ATSR 0.55 micron channel image showing algal bloom extent in the Baltic Sea (courtesy of Clean Seas Project)

Land

Issues such as the influence of surface conditions on atmospheric circulation, water circulation and carbon cycling are at the core of a better understanding of climate processes. Data products from sensors such as MERIS and AATSR, which represent the ratio of radiation in the near-infrared and red wavelengths (e.g. normalized difference vegetation index) are primarily useful to locate vegetation and estimate its amount. Novel experimental products are expected to provide a measure of the boundary position between chlorophyll absorption in the red and leaf scattering in the near-infrared (i.e. red edge) to estimate both chlorophyll concentration and vegetation condition.

It is also a priority to provide data on the spectral structure of the land surface. This data will be obtained by recording wavelengths related to the phenomena of interest, such as chlorophyll concentration, leaf senescence, moisture content and iron content. Of particular interest for the land community is the combination of high spectral and coarse spatial resolution in a frequent repetitive coverage, which is provided by both MERIS and AATSR.

Global land-cover monitoring

Within the biosphere, vegetation is critical, as it not only supports the bulk of human and animal life, but also controls the exchange of water and carbon between the land and the atmosphere.

Spatial and temporal models of the biosphere are currently being developed to study the mechanics of such complex systems, in order to predict their behaviour under changing environmental conditions. These models are based on physical and biophysical relationships, needing validated results on a regular basis from space-borne sensors. Repetitive accurate physical measurements are necessary in order to quantify surface processes and to improve the understanding of vegetation seasonal dynamics and responses to environmental stress. Instrumental to this is the ability to understand the surface structure of vegetation and soils. In this context, the surface bi-directional reflectance distribution function has also to be analysed in data with a high repeat rate and a comparably large swath, enabling the investigation of a target under varying illumination conditions. Surface spectral bi-directional reflectance can be calculated after normalisation to the solar irradiance and atmospheric corrections. Such a high-quality dataset can then be efficiently calibrated against ground data such as leaf-area index, biomass, soil background, etc. A vegetation

index has also been specifically developed for MERIS, giving rise to improved quantitative estimates of the vegetation status and its condition.

The top-of-atmosphere reflectances offered by AATSR and MERIS can also be used in other ways over land. The narrow bands of MERIS will make it possible to derive more accurate global maps and more effective vegetation indices than have previously been available (Fig.10). They will also contribute towards the construction of the accurate albedo maps needed as boundary conditions in meteorological prediction models. Estimates of vegetation parameters such as land-cover type, leaf-area index and biomass concentration can also be derived from the basic reflectances.

Forestry

The Earth's forests play an important role in absorbing carbon dioxide from the planet's atmosphere, and their destruction will contribute to the Greenhouse Effect. On a local scale, deforestation has had dramatic effects on the climate, and the combination of reduced rainfall and soil erosion severely limits the agricultural use of the cleared land, with consequent economic repercussions.

AATSR and MERIS will provide improved capabilities for global and regional forest inventory. For example, clear evidence of the anthropogenic origin of forest destruction can be seen in the ATSR imagery in Figure 11. Regular linear inroads into the forest can be seen, and large cleared areas stand out among the surrounding vegetation. Ground-based estimates of the scale and rate of deforestation are notoriously inaccurate and rapidly become outdated, but satellite images provide a reliable and convenient method for the long-term global monitoring of this phenomenon.

Synergy

The attribute of synchronised observations from two different instruments will be equally valuable for vegetation studies over land. Although the visible/near infrared bands on AATSR are not as narrow as those on MERIS, there is potential for the superior atmospheric correction offered by the dual views to assist in improving estimates of bi-directional reflectance for crop growth and other models. AATSR will offer the added advantage of complementary observations in the thermal channels over land that, whilst not originally designed for this purpose, have proved useful for studies of burning vegetation and the retrieval of land-surface temperature.

Ocean-colour data and information on land vegetation can also be combined to provide views of the whole Earth biosphere (Fig. 12).

Figure 10. Monthly MERIS Global Vegetation Index for June 1998, derived from SeaWiFS images (courtesy of JRC/SAI/GVM)

Figure 11. An ATSR-1 image showing the extent of de-forestation in Brazil (courtesy of RAL)

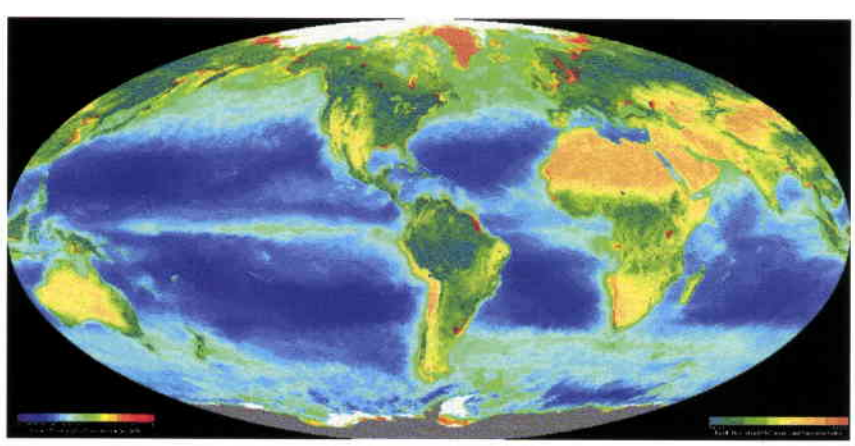

Figure 12. Biosphere globe derived from SeaWiFS images (courtesy of NASA/GSFC and Orbimage)

Figure 13. ATSR image of Typhoon Saomai

Clouds and atmosphere

Cloud parameters

Figure 13 shows a night-time, 11 micron, false-colour image of typhoon Saomai over the East China Sea, heading north towards the Korean Peninsula. In addition to providing information on the basic location, extent and structure of clouds, data from different AATSR channels can be combined to estimate various properties of the cloud field. These include:

- optical depth, which is broadly related to the vertical dimension of the cloud
- phase, which determines whether the cloud contains ice or water
- particle size, which is the effective radiative dimension of the cloud particles, and pressure, which reflects the cloud-top pressure or altitude.

Thanks to the possibility of using narrow spectral bands, MERIS also provides information about cloud amount, cloud type, cloud albedo and cloud-top height, to complement the top-of-atmosphere radiance data. These datasets are of particular value for the validation of the models of radiative transfer in the presence of clouds used in general-circulation models of the atmosphere.

The unique conical scanning mechanism used by the AATSR instrument and the resulting dual view of the Earth also provide a natural stereoscopic view of cloud fields. The stereo view allows discrimination of the different layers and structures within the cloud. The dual view can also be exploited to estimate cloud-top height. By matching sub-scenes from the nadir and forward images, the relative displacement of objects in the two images can be found. Combined with knowledge of the pointing geometry of the two views, this leads to an estimate of the object's height above sea level.

Aerosols

MERIS has the ability to evaluate aerosol properties, including optical thickness and type. Data from ATSR-1 and ATSR-2 have also been used to map stratospheric aerosol distribution, a capability continued with AATSR.

Aerosol optical thickness and aerosol type will be determined over open oceans. The MERIS ground segment will also attempt to perform an aerosol correction over turbid (coastal) waters. This will lead to marine directional reflectances at the air/sea interface, which will be important for deriving other local and regional applications.

MERIS also possesses two channels in the near-infrared dedicated to the measurement of pressure by differential absorption of O_2. This allows the discrimination of optically thick aerosols from clouds. This is particularly important in the tropics, where low cloud cover makes the large absorbing aerosol loads from tropical deserts (Fig. 14) a prime contributor to the radiative forcing of the atmosphere. The aerosol product will be provided systematically and will help resolve the uncertainties associated with the modelling of the radiative forcing of mineral dust. The presence in the same product of aerosol, algal pigment and cloud data is also expected to further the search for correlations between these different parameters over the oceans.

Aerosol properties will also be estimated by MERIS over land, but only over patches of dense dark vegetation. The retrieval of aerosols over land is a very difficult task for an instrument operating in the visible and near-infrared. Aerosol optical thickness and type can only be retrieved over limited land cover types, such as dense forests, the reflectance of which has to be known with confidence. It also requires some a-priori assumptions about the refractive index of the aerosol. Consequently, this will be provided as an experimental product.

Water vapour
The MERIS water-vapour product is a measurement of the concentration of water vapour found in the total atmospheric column. This product is of particular interest over land where the signal, and consequently the precision of this product, is expected to be particularly high. It will also be provided over water surfaces and clouds. Good water-vapour retrieval is also expected over ocean regions affected by Sun-glint. This product will be delivered to ECMWF for assimilation into meteorological models to improve weather forecasting.

Cryosphere
Changes in global sea level are at present related mostly to the global warming of the climate, through the thermal dilatation of the oceans. However, the contribution of the melting of polar ice sheets to rises in sea level is also becoming an important area of research, with particular focus on time-series measurements of changes in floating and grounded ice in Antarctica and Greenland.

AATSR will provide frequent observations of the Antarctic region, coverage of a large proportion of the coastline on a daily basis, and total coverage of the region every three days. Large icebergs, several kilometres or more across, can be identified in the images (Fig. 15) and their dimensions determined. These data provide the basic information needed for an assessment of their spatial distribution, of their calving, breakage and melting rates, and of their movement.

The icebergs represent a major component of the mass discharge from the Antarctic ice sheet, and hence of its overall mass budget. The other large, but poorly known, component of the mass discharge occurs through melting from the base of the floating ice.

Hazard monitoring
Volcanoes
Volcanoes represent serious natural hazards, particularly in developing countries where large populations gather on the highly fertile volcanic soils close to active volcanoes, and where monitoring activities are most limited. The logistics associated with monitoring the vast number of potentially active volcanoes is also a problem.

Satellite remote sensing provides the opportunity to augment traditional monitoring methods. This is particularly true of the ATSR instruments, which will view all of Earth's terrestrial volcanoes once every three days under night-time conditions, which is the ideal time to monitor their thermal activity and detect any eruptive activity (Fig. 16).

Forest fires
Large vegetation fires are a major source of atmospheric pollutants and fire is a key

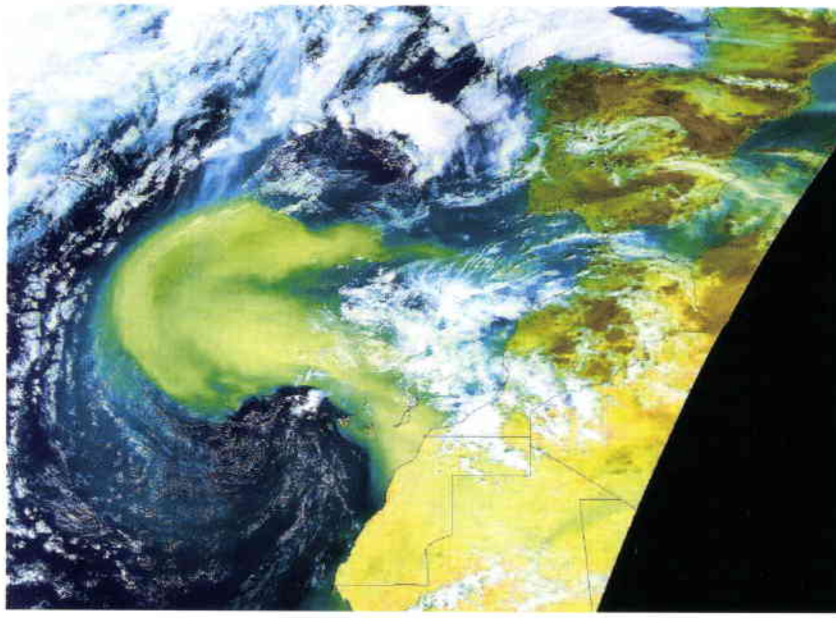

Figure 14. SeaWiFS image of a Saharan dust storm over the Atlantic Ocean west of Morocco, on 28 February 2000 (courtesy of NASA/GSFC and Orbimage)

Figure 15. An ATSR-2 image of the B-15 iceberg as it broke away from the Ross Ice Shelf (courtesy of RAL)

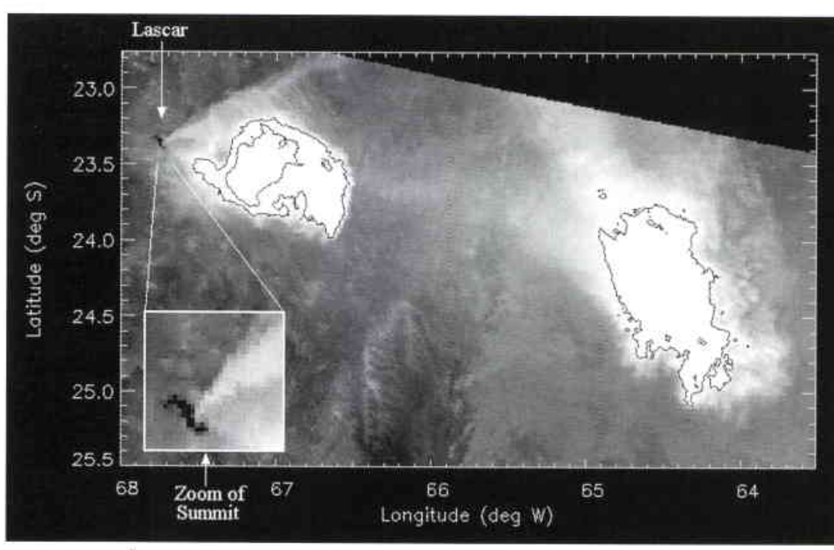

Figure 16. ATSR daytime 11-micron image of the Lascar Volcano, in Northern Chile (courtesy M. Wooster, Kings College London)

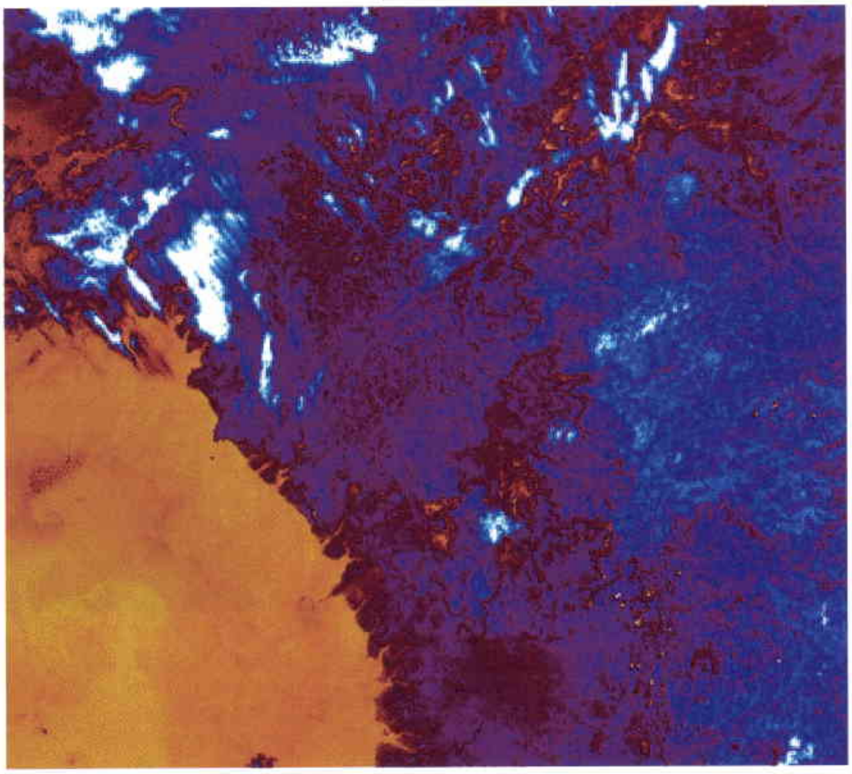

Figure 17. An ATSR night-time image of the West African Coast. The large yellow area is the Atlantic Ocean. The cooler land appears red, and bush fires can be seen as small yellow spots (courtesy of RAL)

Figure 18. SeaWiFS image of smoke plumes over the Gulf of Mexico on 5 June 1998 (courtesy of NASA/GSFC and Orbimage)

indicator of anthropogenic activity and biomass destruction. In some ecosystems, fire is a natural and beneficial land-management tool, but in others it is a major hazard requiring careful monitoring.

ATSR-2 has already demonstrated a capability for detecting fires at night using the 3.7 micron channel (Fig. 17). Visible-channel images from both the AATSR and MERIS will also be useful for detecting smoke plumes (Fig. 18). Time series of images of this kind are particularly valuable for determining the distribution and spread of fires throughout a region, and have also been used to create a global fire atlas.

Conclusion

Both MERIS and AATSR, with their moderate pixel size and large-area imaging abilities, will have an enormous range of potential local, regional or global applications on time scales ranging from days to years. The products to be routinely produced from these instruments have been identified by experts as the most important, globally measurable parameters on which further applications can be built. In addition, the potential for exploitation of AATSR and MERIS data will be underpinned by a rigorous calibration and validation programme that will be undertaken by ESA and the instrument science teams.

The main application of both optical sensors will be in the measurement of biological and physical variables of the ocean, in particular sea-surface temperature and the amount of phytoplankton. This is expected to lead to new insights into the global carbon cycle and processes that shape our climate. Furthermore, the extended objectives of both instruments will be directed to the understanding of atmospheric variables associated with clouds, water vapour and aerosols, with a view to atmosphere and climate modelling. Finally, the global monitoring of land cover and attendant estimates of the state of vegetation or biomass are also important parameters that will contribute to biogeochemical models applied to dynamic processes of global ecosystems and climatic variations.

In the context of growing concern about the future evolution of our climate and the devastation of the natural environment by mankind, MERIS and AATSR will provide data of unique quality and of crucial importance for understanding the mechanisms that control or amplify climate variability, for the improvement of weather forecasts as well as for a rational use of the Earth's resources.

The Radar Altimetry Mission: RA-2, MWR, DORIS and LRR

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The Altimetry mission on Envisat will extend the time series of observations started by ERS-1, and the new features of the RA-2 instrument will improve the quality of the measurements in many respects. The new on-board algorithms for tracking the surface, the larger range window and the extra low-resolution mode will all improve data acquisition over the important ice-sheet margins and over most land and wetland surfaces. New, in-situ ionospheric corrections from the dual radar frequency will be a significant improvement on the model-based corrections used on previous missions. The more precise DORIS orbit will improve the precision of all measurements, particularly in near-real time. The near-real-time products will be built with the same algorithms as the offline final precision products (only some auxiliary input data may differ), thus providing near-high-quality geophysical-data-record products within 3 hours of observation to support near-real-time oceanography.

Introduction

The Radar Altimetry mission encompasses four of the ten instruments on-board Envisat. Its main objective is to ensure continuity of the altimetric observations started with the ERS-1 satellite in 1991. The science mission objectives are similar to those of ERS, but the altimeter record will exceed 15 years in length and will permit changes to be examined on inter-annual to decadal time scales in:
- global and regional sea level
- dynamic ocean-circulation patterns
- significant wave height and wind-speed climatology
- ice-sheet elevation and sea-ice thickness.

Another objective is to provide for the enhancement of the ERS ocean and ice missions, in particular, by improving the quality of the measurements and monitoring capabilities for:
- ocean mesoscale, significant wave height and wind speed in near-real-time
- marine geophysics – polar oceans
- ice-sheet margins – sea ice
- lakes, wetlands and river levels
- land
- ionosphere and water vapour.

The Envisat mission is part of a coherent European Earth-Observation Programme ensuring the long-term provision of continuous data sets, which are essential for addressing environmental and climatological issues. The Altimetry mission is therefore a contribution to such international programmes as the International Geosphere – Biosphere Programme and the World Climate Research Programme. Envisat is also directed at the promotion of applications and the commercial use of Earth-observation altimetry data for operational sea-state and ocean-circulation forecasting.

Oceanographic applications

Oceans cover 70% of our planet and play a key role in regulating the global climate. They are the main reservoir for heat, as well as a powerful vehicle in transporting warm water masses poleward. They have the capacity to take in (but also to reject) significant amounts of carbon dioxide, one of the greenhouse gases. They also allow the cost-effective transportation of goods by ship, they are where we can discover new oil fields, and they are the feeding grounds for the fish and other sea-food needed to nourish Earth's ever-growing human population.

The oceanographic mission objectives for Envisat altimetry, based on the results already obtained with ERS, include the monitoring of dynamic topography, mesoscale variability, seasonal and inter-annual variability, mean global and regional sea-level trends, marine geophysics (especially in polar oceans, even covered with sea-ice), and sea state. These objectives are to be met with data products available either in near-real-time (3 hours), in quasi near-real-time (2-3 days), or with the highest precision offline products.

Seasonal and inter-annual variability has an important impact on climate. Planetary waves propagate from months to seasons across basins to adjust the ocean in response to wind forcing. Inter-annual variations in the seasonal or annual cycles have a direct and sometimes dramatic impact on the global climate, as is well illustrated by the El Niño Southern Oscillation (ENSO) (Fig. 1). The data gathered from space serve to develop and tune global ocean and atmosphere models, in order to better understand the ocean-atmosphere interaction and the underlying processes.

The ocean is vast and generates a whole spectrum of signals that one orbiting satellite alone cannot pretend to cover. There are therefore significant advantages to be gained by merging the data from two or more altimetry missions sampling the Earth with different orbital patterns. A good illustration in this respect is the enrichment in spatial resolution of the mesoscale variability field computed with merged data from ERS and Topex-Poseidon (Fig. 2), which have the same orbital configuration as the Envisat and Jason missions.

Ice and sea-ice applications

Polar ice sheets and sea ice play a vital role in the global climate system, due both to their effectiveness in reflecting incoming solar radiation, and their role as a huge store of fresh water. Sea ice acts as a barrier between the ocean and the atmosphere, cutting off exchanges of heat, moisture and momentum. Brine expulsion during seasonal sea-ice formation and intense cooling of the sea surface through polynyas drive the thermohaline circulation of the oceans. This process creates the dense bottom water in the Pacific, Indian and Atlantic Oceans, and is responsible for the poleward transport of heat in the North Atlantic, which ensures mild winters for Western Europe.

This critical component of the climate system is not well represented in current climate models, but is clearly important if accurate predictions

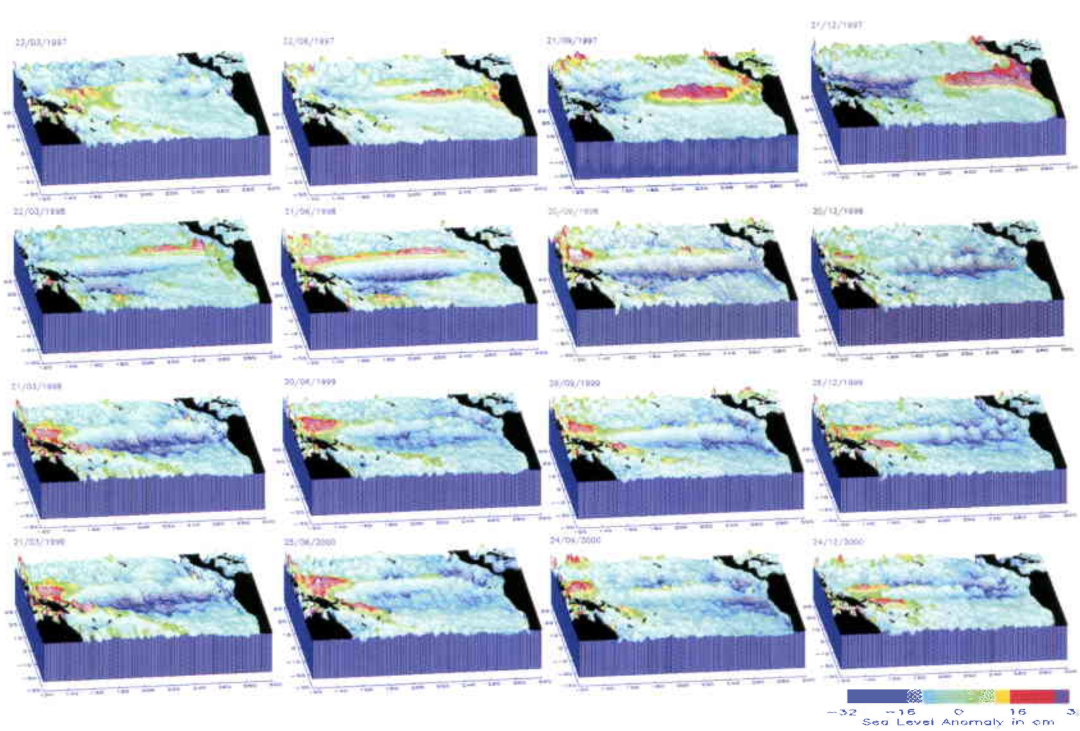

Figure 1. Series of sea-level-anomaly (cm) data for the tropical Pacific Ocean. Each row is for one year (1997 - 2000) with one sea-level-anomaly field sample each season, by column: March, June, September and December. The strong El Niño event of late-1997 followed by a La Niña event is clearly visible. A film of such 3D vignettes helps researchers to visualise the wave propagation involved in such events. Each weekly field can be assimilated into an ocean model (SLA data processed by R. Scharroo, DEOS, NL; graphics processed at ESA/ESRIN)

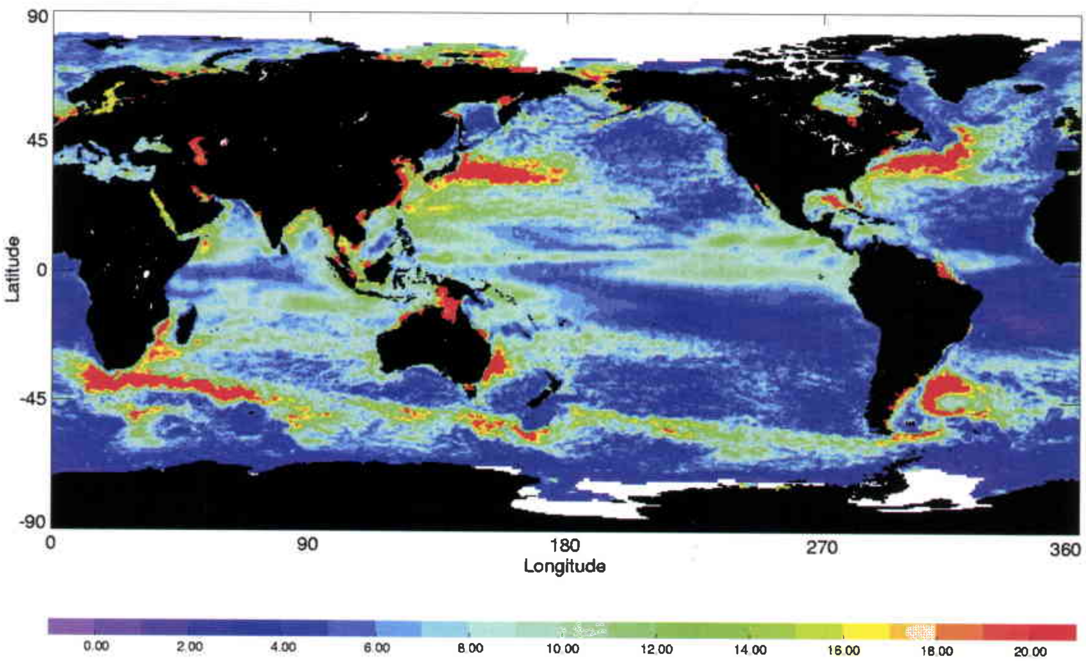

Figure 2. Root-mean-square of sea-level anomaly (in cm) obtained from merged ERS and Topex-Poseidon data from October 1992 to October 1997. Note the high resolution of the map brought by the denser ground-track mesh of ERS (courtesy of P.Y. LeTraon, CLS)

of the consequences of global warming are to be made. Global warming is predicted to be greatest in the Arctic region, and if Arctic sea-ice is lost it could change the circulation pattern of the North Atlantic, resulting in severe winters for Western Europe. Melting of the Greenland and Antarctic ice sheets would contribute to a rise in global sea level.

The vast, remote and inhospitable polar regions can only be monitored effectively through a global remote-sensing system. Polar regions experience between 50 and 90% cloud cover and spend long periods in darkness, which limits optical and thermal-infrared instrument observations. Fortunately, this task is particularly well served by satellite-borne active radar instruments.

Techniques developed using the ERS Radar Altimeters have allowed the monitoring of ice-sheet mass balance and the derivation of sea-ice thickness through the measurement of freeboard. Continuous altimetric measurement of the Antarctic ice sheet since 1992 has revealed for the first time a significant thinning of a West Antarctic glacier (Fig. 3). The Pine Island Glacier has retreated, and has thinned inland by as much as 10 metres. It is important to continue this monitoring with the Envisat RA-2 instrument to establish whether this retreat will accelerate the mass discharge from the West Antarctic ice sheet.

Balance velocities (the depth-averaged velocity required to maintain the ice sheet in a state of balance at a given point for a given surface mass flux) have been estimated over the Antarctic grounded ice sheet using ERS Altimeter data (Fig. 4). These balance velocities depend mainly on the surface slope and are modulated by surface mass balance and ice thickness. Their study contributes to our understanding of ice-sheet dynamics and its response to climatic forcing.

Sea-ice thickness can be sampled using moored or submarine-mounted Upward Looking Sonar (ULS). Moored ULS only samples a fixed location, and submarines tend to sample limited areas for only a few weeks each year. This is not sufficient to deduce full regional and seasonal variations. Freeboard measurement by satellite is the only technique

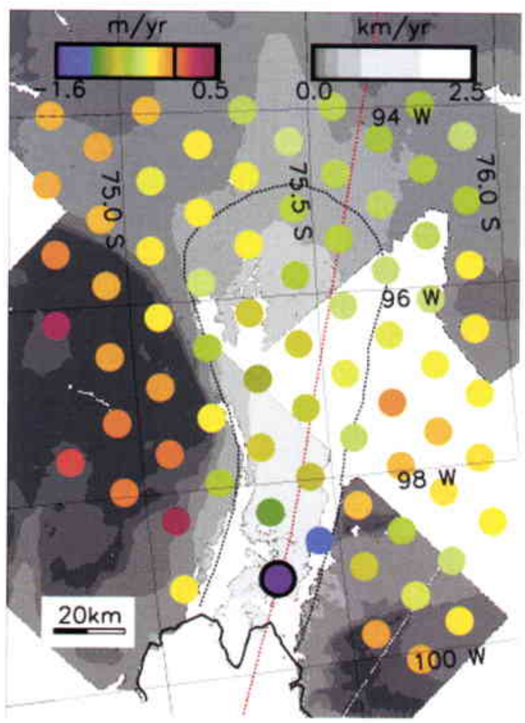

Figure 3. Rate of elevation change of the lower 200 km of the Pine Island Glacier. The coloured dots are located at crossover points and have an area equal to the RA footprint. The grey shading is the velocity field derived from ERS SAR data (courtesy of MSSL/UCL)

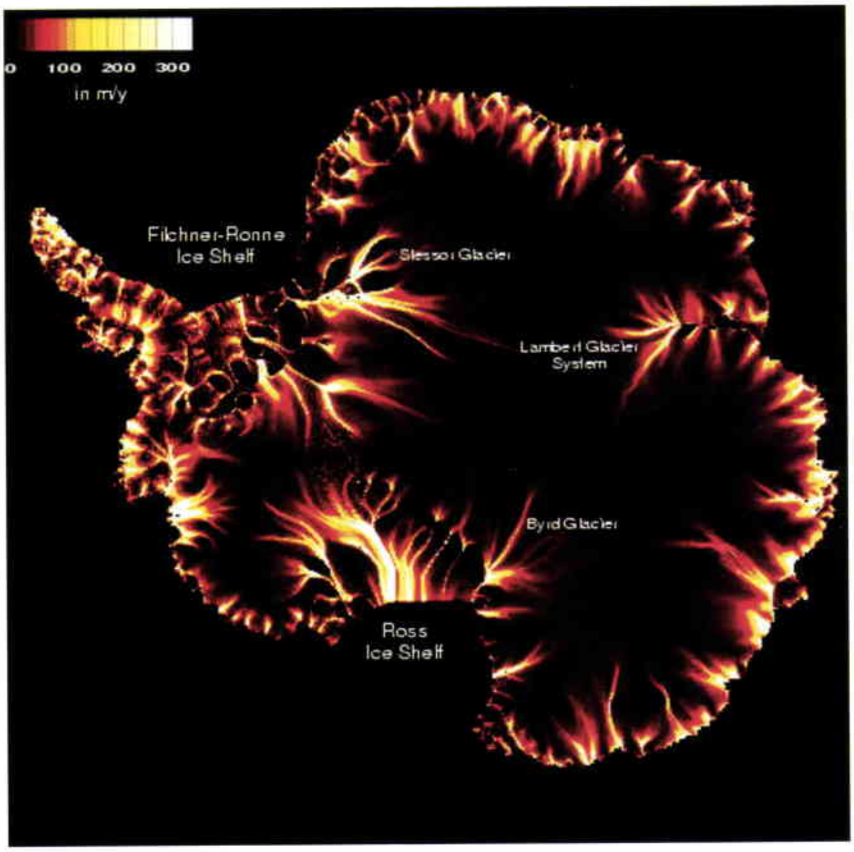

Figure 4. Balance velocities estimated from ERS Altimeter data (courtesy of F. Remy, LEGOS)

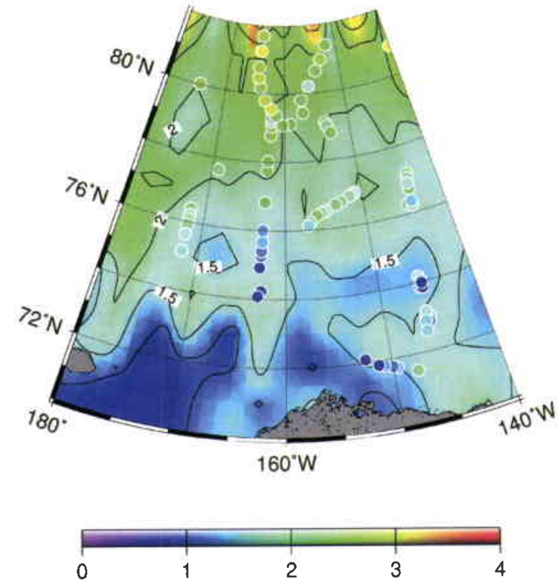

Figure 5. A comparison between RA-derived sea-ice thickness (m) and sparse measurements from ULS on submarines (dots), in October 1996 (courtesy of MSSL/UCL)

that can measure sea-ice thickness on the time and length scales that climate investigation demands. The technique has been developed using ERS Altimeter data, has been verified using the ULS measurements, and will be implemented in Envisat's RA-2 ground processing. Results from ERS suggest that the recently reported thinning of Arctic sea ice may be localised (Fig. 5), and continued monitoring using RA-2 is critical to establish long-term trends.

The Envisat Altimetry mission will both extend and improve the monitoring of the cryosphere in the climatically important polar regions.

Land applications

Over land, the Radar Altimeter echoes have a non-predictable shape, which is why its land-based applications have matured only slowly and painstakingly. One remarkable result from the ERS-1 geodetic phase is the Altimeter Corrected Elevation Model (ACE), which replaces more than 28 % of the most precise global Digital Elevation Model with an Altimeter-derived height dataset and corrects another 17% (Fig. 6). The Envisat Altimeter, even though it will not fly an orbit as dense as the ERS-1 geodetic mission, will improve on this result in terms of accuracy and by including

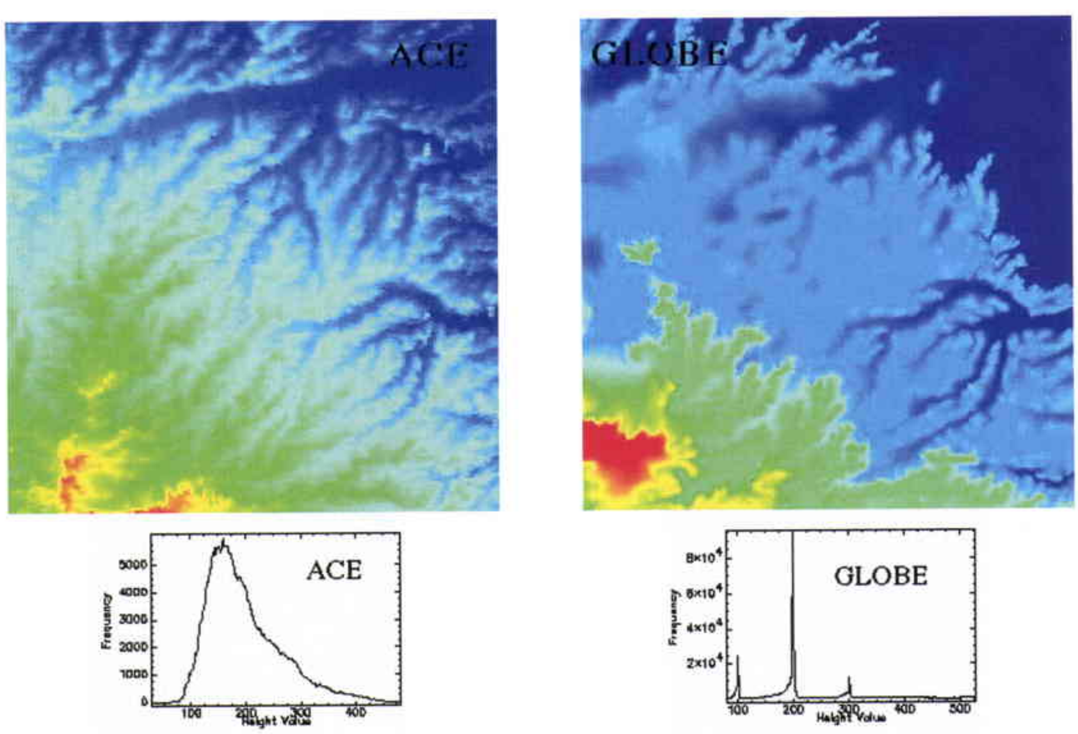

Figure 6. Comparison of the ERS Altimeter-derived map (ACE) of part of the Amazon Basin with the GLOBE map of the same area (73-68 W, 11-6 S). Note the 100 m contours in the GLOBE histogram and the fine (rich histogram) detail in the ACE product (courtesy of Prof. Ph. Berry, De Montfort University, UK)

new areas never before measured. The newly generated ACE product, released at the end of February, forms part of the market-development activity within the ESA Earth-Observation Envelope Programme.

Another land application that has been painstakingly attempted since Seasat is river- and lake-level monitoring. Radar altimetry is a powerful tool for this application as it unifies all river- and lake-level measurements around the world, even for the most remote or inaccessible regions, with a unique gauge. Being able to measure the global river levels, be it only once or twice a month, would be a significant contribution to hydrology.

It has been demonstrated with the ERS Altimeter that echoes from an inland water surface are clearly discernible and convertible to river or lake levels. The inclusion of an Ice mode on ERS-1 and ERS-2 has led to a huge increase in the percentage of the Earth's land surfaces from which valid altimeter echoes have been obtained. This has also resulted in coverage of the majority of the world's river systems, raising the exciting possibility of a 10-year time series of river-height data. The inclusion of a third tracking mode on Envisat should further increase the land hydrology potential of altimetry with even greater river coverage, as well as continuing the hydrology time series. To illustrate the ERS/Envisat contribution, Figure 7 shows part of the Amazon River system, with crossings from the ERS-1 geodetic phase superimposed on an altimeter-derived river map.

Envisat altimetry mission characteristics

Envisat will cover high-latitude ocean, ice-sheet and land-surface areas not covered by the Topex/Poseidon, GFO or Jason missions. The 35-day repeat cycle, on the same ground track as ERS-2, allows for dense cross-track spacing and optimum synergistic combinations with the simultaneously operating Jason/GFO altimetric missions for a wide range of applications. The advantages of this have already been clearly demonstrated by combining current ERS mission data with data from Topex/Poseidon. The orbital characteristics for Envisat are summarised in Table 1.

Table 1. Envisat orbit characteristics

Orbit type:	Sun-synchronous
Ascending node:	22:00 MLST
Inclination:	98.5°
Altitude:	~ 800 km
Orbits per day:	14 11/35
Repeat period:	35 days (501 orbits)
Equatorial ground-track spacing:	~80 km
Ground-track repeat:	±1 km

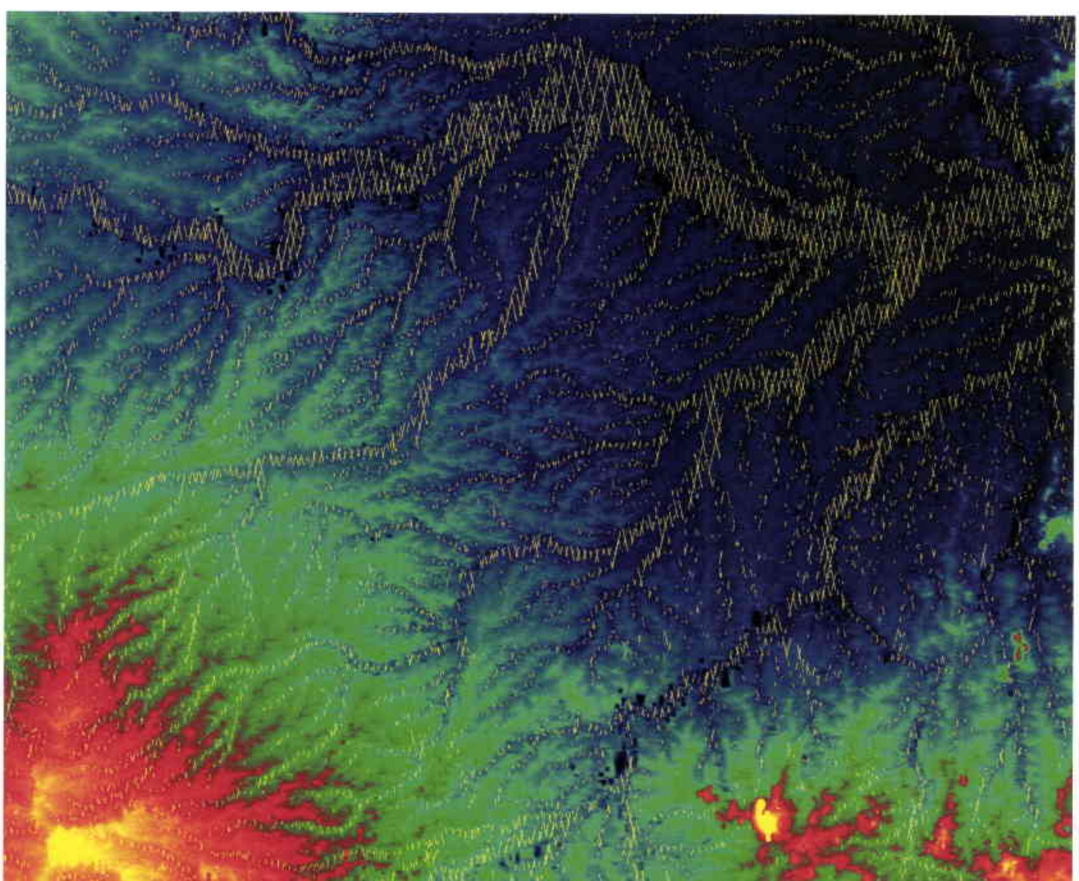

Figure 7. River echoes superimposed on high-resolution ERS-1 Altimeter-derived topography and river network. The plot shows a 11° x 12 ° area of South America containing part of the Amazon Basin (15-4 S, 75-63 W) with the ACE GDEM heights (high: yellow through red; low: green to dark blue) overlaid with ERS-1 Geodetic Mission 'water-type' returns in bright yellow. Note that this part of the ACE GDEM is totally derived from altimetry, which has provided a huge increase in spatial and vertical resolution over previous GDEM models for this region rich in river networks (courtesy of Prof. Ph. Berry, De Montfort University, UK)

The Envisat altimetry payload

The instrument set is composed of:
- RA-2: a multi-resolution, self-adaptive, dual-frequency radar altimeter
- MWR: a dual-frequency nadir-viewing microwave radiometer
- DORIS: a dual-frequency Doppler tracking system for orbit estimation
- LRR: a laser retro-reflector for tracking.

RA-2

Radar Altimeter-2 belongs to a new generation of radar altimeters. One of the major improvements with respect to the ERS RA lies in its second frequency (3.2 GHz, S-band) allowing compensation of the delay due to ionospheric electron density. It is designed for low height noise (pulse repetition frequency of 1795 Hz) and improved wave-height accuracy, with two additional bins on the echo leading edge. Its tracking follows a novel strategy allowing robust on-board collection of accurately quantified radar echoes over all surfaces. Another new feature is the Model Free Tracker, which is robust at handling non-ocean-like echoes, sampled over 128 bins.

RA-2 has three different range resolutions, adapted to different sensing scenarios (ocean, ice sheets, sea ice, wetlands, ice edge and land) and thus to avoiding losing track. Whereas previous altimeters have suffered data dropouts over areas with difficult terrain, RA-2 will be more robust, providing valuable data for applications involving ice edges, land, lakes, wetlands and coastal zones. The switching is controlled autonomously. RA-2 has the ability to preserve a small amount of individual echoes (unaveraged echoes, at 1795 Hz), which are useful for engineering and scientific studies.

Table 2. The three different resolution modes of RA-2

Bandwidth (MHz)	**Resolution (m)**	**Range window (m)**
320	0.5	64
80	2	256
20	8	1024

No geophysical-parameter estimation is performed on-board, where computer resources are limited and fully dedicated to collecting high-quality echoes, and so re-tracking is applied on the ground to create each product, including those delivered in near-real-time. To optimise retrieval for each kind of surface, the waveforms are processed in different complementary manners: four re-trackers – ocean, sea-ice, ice 1, ice 2 – are run in parallel all the time (over all surfaces). Their outputs are delivered in the Geophysical Data Record (GDR) product and in the waveform product (SGDR). Land echoes are so complex, diverse and unpredictable that they cannot be handled by a single re-tracker: the land-applications users will access the waveforms. More details on instrument operation and performance can be found in ESA Bulletin No. 98.

MWR

The Microwave Radiometer's primary mission is determination of the tropospheric-water-vapour path-delay correction for RA-2. Additional applications of MWR data include surface emissivity, ice-sheet dynamics, sea-ice mapping and land-surface temperature, but imaging radiometers are rather used for these applications. The Envisat MWR has the same concept and specification as the two ERS MWRs, but is of a new design. The MWR shares its Instrument Control Unit with DORIS (was ATSR on ERS). It is a dual-frequency, Dicke radiometer (1 kHz switch frequency), with near-nadir viewing using an offset parabola antenna and two feeds (the parabola is fixed, whereas it needed deployment on ERS). Calibration, which is based on a sky-horn (cold load) and an internal hot load, will be performed about twice per minute.

All MWR measurements are to be delivered with the RA-2 products, as so-called RA-2/MWR data products. Further details can be found in ESA Bulletin No. 104.

Table 3. MWR characteristics

Frequency:	23.8 GHz	36.5 GHz
Bandwidth:	400 MHz	400 MHz
Polarisation:	Linear	
Integration time:	150 ms	150 ms
Dynamic range:	3 – 313 K	3 – 313 K
Footprint size:	20.5 km	19.2 km
Footprint centre:	25 km behind	35 km ahead
Sensitivity:	0.6 K	0.6 K
Absolute accuracy:	< 3 K	< 3 K
Data rate:	0.427 kbps	

DORIS

The Doppler Orbitography and Radio-positioning Integrated by Satellite system was developed by CNES (Centre National d'Etudes Spatiales), IGN (Institut Géographique National) and GRGS (Groupe de Recherche en Géodésie Spatiale) to meet scientific and operational user requirements in very precise orbit determination. The basic principle of the DORIS system and its capabilities on Envisat were explained in some detail in ESA Bulletin No. 104.

Designed and optimised to provide high-precision orbit determination and beacon positioning, DORIS was developed in the framework of the Topex/Poseidon (T/P) oceanographic Altimetry mission. Operational since 1990 when the Spot-2 satellite was launched, it is an uplink radio system based on the Doppler principle. It measures the relative velocity between the orbiting satellite and a dense, permanent network of orbit-determination beacons, which form the core of the system and are distributed homogeneously over the Earth. The DORIS permanent network includes 54 beacons hosted by institutes from more than 30 different countries. More than 20 beacons are collocated with other precise positioning systems to allow cross-calibration. The dual-frequency signals at 400 MHz and 2 GHz emitted by the beacons are used by the receivers on-board the various satellites to perform Doppler measurements. Within the network, two master beacons, located in Toulouse (F) and Kourou (Fr. Guiana) are connected to the control centre to allow data uploading to the on-board package, and are also linked to an atomic clock to allow synchronisation of the DORIS system with international reference time.

The DORIS package on-board Envisat includes: a receiver performing Doppler measurements and receiving auxiliary data from the beacons, a bi-frequency omni-directional antenna, an Ultra-Stable Oscillator, and a two-channel receiver with DIODE navigator capability as part of the on-board software. The bi-channel receiver allows two beacons to be tracked simultaneously.

The DORIS Control and Processing Centre, located in Toulouse, is in charge of: beacon network monitoring, on-board package monitoring and programming, science telemetry acquisition and pre-processing, technological archiving, precise orbit determination, and beacon positioning. This Centre is also part of the SSALTO (Orbitography and Altimetry Multi-mission Centre) CNES ground segment. Interfaces between SSALTO and the Envisat Flight Operations Segment and Payload Data Segment have been defined to meet all Envisat mission requirements.

For Envisat, the accuracy of the real-time orbit provided by the DORIS/DIODE onboard software has been specified as 1 m (on three axes). The performance of the DIODE software on Spot-4 and subsequent improvements that have been tested on the ground indicate that this level of accuracy should be reached without difficulty. In fact, various simulations of the radial component of the Envisat orbit indicate that DIODE real-time navigation to the 30 cm level can be achieved using an upgraded version of the software. The Altimeter real-time products will certainly benefit from such a high-quality real-time orbit determination.

The accuracy of the radial component of the offline precise orbit has been specified at the 10 cm level, with the even more challenging figure of 3 cm often quoted as a goal. Experience with Topex/Poseidon and the Spot satellites indicates that the 10 cm target will be reached with no major difficulty, whereas the 3 cm goal is a challenge that the Envisat Precise Orbit Determination (POD) team will actively pursue. The Jason-1 POD group and the other geodetic-mission teams (e.g. CHAMP, GOCE, and GRACE) will help in optimising orbit computation using DORIS and laser tracking measurements.

Within the climate-change research framework, the rate of present-day global sea-level change is a crucial topic, to which DORIS can contribute in several areas, such as: the geodetic reference frame, horizontal and vertical motions of beacons entering the terrestrial reference frame, variations in the geocentre, altimeter calibration using tide gauges, etc. During the Envisat mission, DORIS will also be flying on at least two other satellites, namely Jason-1 and Spot-5. This will ensure the achievement of the required performances in terms of absolute positioning of the DORIS beacons participating in the terrestrial reference frame, leading in turn to an improved final Envisat orbit-error budget. More generally, observation of the ocean is now thought of more and more by oceanographers in terms of a global and 'integrated' system. Indeed, there is now a general understanding that space and in-situ techniques are complementary in terms of the characteristics of the observation techniques, sampling, precision and accuracy, and that they must be exploited in a joint way to provide the optimum observing system.

For a few years already, the GPS and DORIS geodetic techniques have been used together with Altimetry and tide gauges to estimate the rate of sea-level change. The continuous enhancement of the DORIS ground network by multiplying the co-location of DORIS beacons with tide gauges is very favourable. Upgraded versions of the DORIS system, for instance through the multiple-channel capability, now offer the possibility to design an efficient integrated 'tide-gauge + GPS + DORIS + altimetry + laser' sea-level system. It is the intention that the Envisat Altimetry mission, including DORIS and LRR for precise positioning, should play a significant role in this global integrated observing system.

LRR

A Laser Retro-Reflector is mounted on the Earth-facing panel of Envisat close to the RA-2 antenna to support satellite ranging for precise orbit determination and RA-2 range measurement calibration. Laser tracking provides the distance between the spacecraft and the station and is assimilated in precise orbit determination. It will be used extensively during the commissioning phase and regularly during the mission to verify the stability of the positioning system.

The LRR is a passive device that will be used as a reflector by ground-based laser ranging stations using high-power pulsed lasers. The operating principle is to measure, on the ground, the round-trip time of laser pulses reflected from the LRR. The 2 kg LRR is composed of corner-cubes designed to reflect the incident laser beam back directly, making the reflected beam parallel to the incident beam within a few arcseconds. The corner-cubes, made of highest-quality fused silica, work in the visible part of the spectrum at two specified wavelengths: 694 and 532 nm. They are mounted symmetrically on a hemispherical housing, with one nadir-looking corner-cube in the centre, surrounded by an angled ring of eight corner-cubes (Fig. 8). This will allow laser ranging with field-of-view angles of 360° in azimuth and 60° in elevation around the satellite nadir.

The LRR was developed by Aerospatiale (F).

Figure 8. The Envisat Laser Retro-Reflector (courtesy of Aerospatiale)

RA-2/MWR data products

Based on the experience from the ERS missions, significant improvements have been built into this new generation of altimetric products, particularly in terms of the enhanced quality of the near-real-time observations, which will be almost as accurate as the final precise product. The product-specification process has included wide consultation with users of ERS and Topex/Poseidon altimetric data. Further product refinement and state-of-the-art algorithm specification were conducted with the help of three European Expert Support Laboratories (ESLs): Alenia Aerospazio (I), Collecte Localisation Satellites (F) and Mullard Space Science Laboratory (UK).

The algorithm specifications were validated by prototyping within the ESL. Once verified, ESL prototypes became reference processors to produce test data sets designed to validate the ground-segment Instrument-data Processing Facility (IPF). Moreover, the RA-2 and MWR products and algorithms were peer-reviewed by dedicated experts and were the subject of an open review at the Envisat Altimetry Products and Algorithms Review Workshop held at ESRIN in Frascati in June 1999.

The EnviSat RA-2 and MWR Data Products will have – already available in near-real-time – global coverage, the wet tropospheric correction from the microwave radiometer and the ionospheric correction from the two frequencies, as well as many other improvements coming from the novel design of second-generation Radar Altimeter. The comprehensive near-real-time processing runs the same algorithms as for the offline products, with only the availability and quality of the auxiliary data differing.

The suite of products is based on one main Geophysical Data Record (GDR) product. The Envisat general product format is exploited to add sub-structure inside the product to hold additional data such as the averaged waveforms (at 18 Hz), the individual waveforms (at 1800 Hz) and the Microwave Radiometer data set. Thus, the waveform data product (SGDR) is a superset containing the same geophysical data records as the GDR, but with waveform data sets appended. Moreover, these products are global, independent of the sub-satellite terrain and of the Radar Altimeter measurement resolution mode, thus avoiding artificial boundaries between geographical features like land/sea, land/ice or land/lake transitions, and ensuring that ocean, land, ice, lake or wetland data always ends up in the same (unique, global) data product.

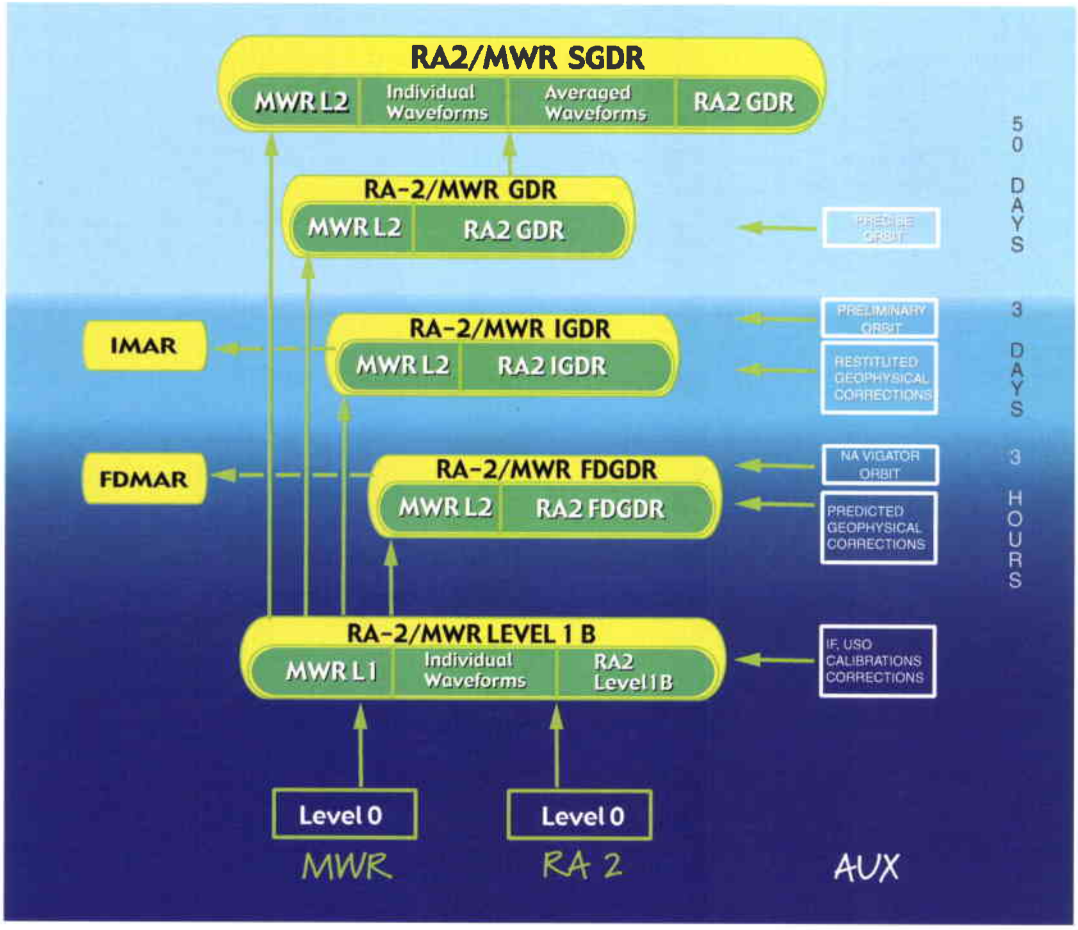

Figure 9. The Radar Altimeter and Microwave Radiometer product tree

The Fast Delivery GDR (FDGDR) product is transmitted in less than three hours, for weather-forecasting, sea-state and real-time ocean-circulation applications. An ocean-related parameter subset of the FDGDR called FDMAR (for Marine Abridged Record) is extracted to reduce the volume of on-line data transfers. FDMAR is converted into the BUFR format commonly used by Meteorological Offices. Less than three days later, the so-called Interim GDR (IGDR) for ocean-circulation monitoring and forecasting applications is delivered, replacing the original meteorological predictions with more precise analyses, and the preliminary orbit with an improved orbit solution. The final GDR and SGDR products containing the most precise instrument calibrations and orbit solutions are delivered after 30 days (not more than 50 days). The schematic in Figure 9 summarises the organisation, the inter-relationships and latency of the product generation. The terminology used to name products is based on the nomenclature traditionally used in altimetry, with the product names stored in the first field of the specific product header.

The Envisat products (identified by their 'Product ID') are categorised into three distinct levels:

- Level 0 (raw): unprocessed data as it comes from the instrument.
- Level 1b (engineering): data converted to engineering units, with instrumental calibration applied (IF filtering, to correct power distortions of echo waveforms, internal range calibrations, corrections for possible drift of reference timing source, no re-tracking); the half-orbit segmented (pole-to pole) product mainly contains: datation (conversion of satellite time to UTC), geo-location, time delay, orbit (<50 cm NRT to ~3 cm offline), sigma-zero, averaged wave-form samples at 18 Hz data rate, individual waveform at full pulse repetition frequency and MWR brightness temperatures.
- Level 2 (geophysical): data converted to geophysical units (with re-tracking); the product mainly contains datation, geo-location, output from re-trackers (range, wind speed, significant wave height, etc.), at 1 Hz plus some 18 Hz parameters (range, orbit). All geophysical products, including the near-real time products, are re-tracked (waveform data are fully processed in the ground processor to extract the geophysical parameters). In order to retrieve the geophysical parameters over all types of surface (ocean, ice, sea-ice, etc.), four specialised re-trackers are continuously run in parallel (over all surfaces):
  - Ocean re-tracker: optimised for ocean surfaces, and based on a modification of the Hayne model

- Ice-1 re-tracker: optimised for general continental ice sheets, it is a model-free re-tracker called the 'Offset Centre of Gravity Echo Model'; it is used for ERS and will ensure measurement continuity
- Ice-2 re-tracker: optimised for ocean-like echoes from continental ice-sheet interior, it is a Brown-based model re-tracking algorithm
- Sea-Ice re-tracker: optimised for specular returns from sea-ice, it is a threshold re-tracking scheme for peaky waveforms.

The usual necessary geophysical corrections are available in the Level-2 products. The ionospheric correction will come from the dual-frequency altimeter, backed-up by the measu-rements from DORIS and the Bent model. The wet tropospheric correction will come from the on-board microwave radiometer, backed-up by a value computed from ECMWF fields. Users requiring the Altimeter waveforms will find them conveniently stored in the Level-2 SGDR product, along with the co-located geophysical corrections and the outputs of the four re-trackers. In other words, the SGDR holds the GDR data augmented by averaged and individual waveforms. Therefore, users of Envisat Altimetry need not access the Level-1b products.

The Fast Delivery data (FDGDR) will be processed at the receiving stations and delivered in less than 3 hours. The Interim Geophysical Data Record (IGDR) and the final precision Geophysical Data Record (GDR) products will be processed offline at the French Processing and Archiving Centre in Toulouse, the so-called F-PAC, with the same algorithms as the Fast Delivery processor. The SGDR is also built at F-PAC.

Envisat User Services will be a unique interface with the user community to provide the required geophysical data products. They will register the data requests, both Fast Delivery and Offline, and organise the acquisition, processing and product delivery. They will be accessible using a WWW browser via a Unified User Services Interface, which will be identical at all stations and centres. Under the new Envisat Data Policy, users of Earth-observation data for scientific purposes will be granted special Category-1 status. These users are invited to submit a research project proposal at any time via the web site http://projects.esa-ao.org (the new data policy is detailed herein). All other, so-called Category 2, users are invited to contact the commercial distributors.

Sample data covering the whole suite of RA-2/MWR products have been distributed on CD-ROM, including a Java display tool known as 'Enviview'. Batch (no graphical user interface) read-write software in C, Fortran and IDL, containing all the RA-2/MWR data set structures, is also available on request.

Conclusion

The Envisat Radar Altimeter mission, including its support instruments, MWR, DORIS and LRR, will serve a myriad of mission objectives, covering oceanographic, cryospheric and land applications. The new-generation Radar Altimeter-2 has many new capabilities to enhance the quality of its measurements, including a second frequency and additional echo sampling near the leading edge for more accurate reading of wave heights. It will be able to make previously impossible measurements over very difficult terrain, using three resolution modes and autonomous switching.

The Geophysical Data Record (GDR) products will be built up from four specialised re-trackers running in parallel over all surfaces. They will be global in nature, with no artificial boundaries, and will be common to the waveform product (SGDR). The data coverage will be up to 81.5 deg N and S in a dense ground-track layout (35-day repeat cycle). The Envisat ground system will deliver global near-real-time data in less than 3 hours. These products will already be of near-GDR quality, as they will be built running the same algorithms as the final precise GDRs. They will contain the good-quality orbit produced in real time by the DORIS navigator and the MWR corrections, and will permit accurate real-time monitoring of global oceanographic signals, contributing to such major near-real-time applications as the Global Ocean Data Assimilation Experiment (GODAE).

The full exploitation of RA-2 data demands high-quality absolute calibration at Ku- and S-band for the three instrument parameters, as well as a very accurate cross-calibration with previous altimeter data during overlapping flights. The objective is to provide the user community with a continuous and consistent altimetric time series (see article on calibration and validation elsewhere in this Bulletin).

Acknowledgements

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The Atmospheric Instruments and Their Applications: GOMOS, MIPAS and SCIAMACHY

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Alarming reports on the impact of human activities on the stratospheric ozone layer, on the evolution of the global climate and on the increasing pollution of the troposphere have attracted considerable public interest during the past two decades. In an effort to try to understand the underlying chemical and physical processes and the role of anthropogenic gas emissions, the scientific community expressed a clear need for a global atmospheric observation platform. In response, a suite of three instruments dedicated to the monitoring of the lower and middle atmosphere have been embarked on ESA's polar-orbiting Envisat satellite.

These three instruments – GOMOS, MIPAS and SCIAMACHY – not only represent a continuation of the atmospheric ozone-monitoring mission of ERS-2/GOME, but significantly enrich the scope of the observational capabilities – mainly the number of detectable species and their vertical distribution – by making use of a variety of novel measurement techniques and enhanced spectral coverage. Their geophysical products will comprise a large number of atmospheric-state parameters, primarily trace-gas abundances, and will establish a high degree of complementarity in the information provided. Together, these data will give the user community unprecedented insight into the atmosphere's chemical and physical processes and facilitate major steps forward towards a better understanding of the future evolution of its chemical and climatological balance.

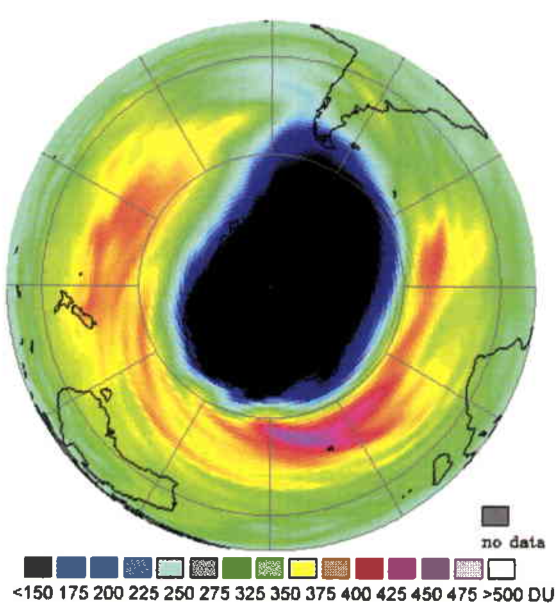


Figure 1. The ozone hole above Antarctica on 22 September 2000, from ERS-2/GOME data (courtesy of KNMI, The Netherlands)

Envisat's atmospheric instruments: scientific rationale and mission objectives

The study of chemical and dynamical processes in the Earth's atmosphere has become of growing interest to researchers in various scientific disciplines within the past two decades. This reflects a growing public concern regarding the consequences of mankind's activities, such as:
- the dramatic ozone depletion in the Antarctic spring atmosphere, first observed in the mid-1980s
- the global warming of the lower atmosphere
- the increased pollution of the troposphere, particularly over industrial regions and biomass-burning areas.

Significant efforts have been undertaken to improve our understanding of the underlying chemical and physical processes and to establish reliable strategies for forecasting the future evolution of key atmospheric-state parameters. Various basic mechanisms, notably the catalytic destruction of stratospheric ozone due to the intake of chlorine compounds and the role of so-called 'greenhouse gases' in the Earth's radiation balance, were soon identified and led to international resolutions, such as the Montreal Protocol, seeking to limit the world-wide release of CFCs. It was, however, recognised that comprehensive modelling of the Earth's atmospheric system that takes into account primary chemical and physical interactions, relies critically on the availability of co-located, global measurements of various key trace gases, and that such measurements could best be realised by dedicated sensors carried on a (near-)polar-orbiting satellite. This concept had been exploited and successfully demonstrated by the Global Ozone Monitoring Experiment (GOME), on board Envisat's predecessor satellite ERS-2, which has been delivering total ozone column measurements since its launch in 1995 (Fig. 1).

An enhanced satellite-based observation platform should focus on a number of research objectives, in particular:
- stratospheric ozone chemistry/destruction cycles
- the role of increasing loads of chemically active species (NO_x, CO, CH_4) and of CFCs in the chemistry of the lower and middle atmosphere
- tropospheric/stratospheric exchange processes
- long-term monitoring of greenhouse gases (H_2O, CH_4, N_2O, CO_2, CFCs) and their impact on global climate
- dynamical processes in the stratosphere.

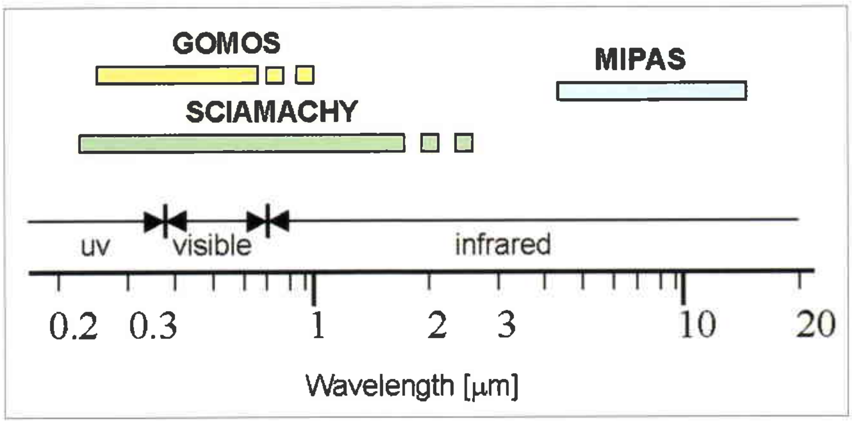


Figure 2. Spectral coverages of Envisat's atmospheric sensors

In response to the observational requirements formulated by a wide scientific community, a number of options for the implementation of an atmospheric mission were investigated. However, it was soon recognised that a single instrument, exploiting a single detection technique, would not be capable of serving all primary needs, both in terms of detectable species and of geographical and height range coverage. Instead, a suite of three atmospheric instruments was finally selected for Envisat:
- GOMOS (Global Ozone Monitoring by Occultation of Stars), a medium-resolution star-occultation spectrometer operating in the UV-visible-near-infrared spectral range. This instrument will primarily supply accurate middle-atmosphere ozone abundances and allow precise monitoring of global ozone throughout the mission's lifetime. Optimum performance will be achieved at altitudes between 15 and 80 km and under night-time conditions, whereas the effective sensitivity is a function of brightness and spectral characteristics of the actually tracked target star.
- MIPAS (Michelson Interferometer for Passive Atmospheric Sounding), a Fourier transform spectrometer detecting the Earth's limb emission in the mid-infrared. MIPAS will provide accurate vertical profiles of atmospheric temperature and a number of key trace gases, including the entire NO_x family (except NO_3), and cover a height range from the upper troposphere to the lower mesosphere. As MIPAS detects the atmosphere's thermal emission, it is independent of sunlight conditions ('day- and night-side' measurements) and provides global coverage.
- SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography), a UV – visible – near-infrared spectrometer allowing observations in nadir, limb-emission and solar-occultation mode. Due to its novel observational strategy, it allows retrieval of both total vertical column densities and stratospheric concentration profiles of a number of target species. SCIAMACHY, although depending on solar illumination conditions, will be the only instrument to supply tropospheric column-density information for the primary target gases.

The spectral coverage provided by the three instruments is illustrated in Figure 2.

The three sensors together will allow unprecedented observations from the troposphere up into the mesosphere by combining novel, powerful measurement techniques with large spectral coverage – ranging from ultraviolet to mid-infrared wavelengths – and global detection capabilities.

On a routine basis, the instruments will deliver global measurements of a number of primary geophysical parameters, in particular:
- vertical temperature/pressure profiles ranging from the upper troposphere to the lower mesosphere
- abundancy profiles of molecular species (O_3, H_2O, CH_4, N_2O, NO_2, NO_3, HNO_3, CO, O_2 and BrO)
- vertical total column densities of a number of target species, and information on clouds and aerosols.

In addition to the above 'standard' products that will be processed and disseminated on a regular basis, various other species will be observable, taking advantage of dedicated, enhanced data-analysis techniques.

Instrument concepts and observational strategies

GOMOS

Instrument design

GOMOS operates in the ultraviolet, visible and near-infrared spectral regions and exploits a stellar occultation technique for the detection of atmospheric ozone and other trace gases. The measurement principle allows the acquisition of spatially high-resolution atmospheric transmission spectra. These spectra are computed as the ratio between the undisturbed spectrum

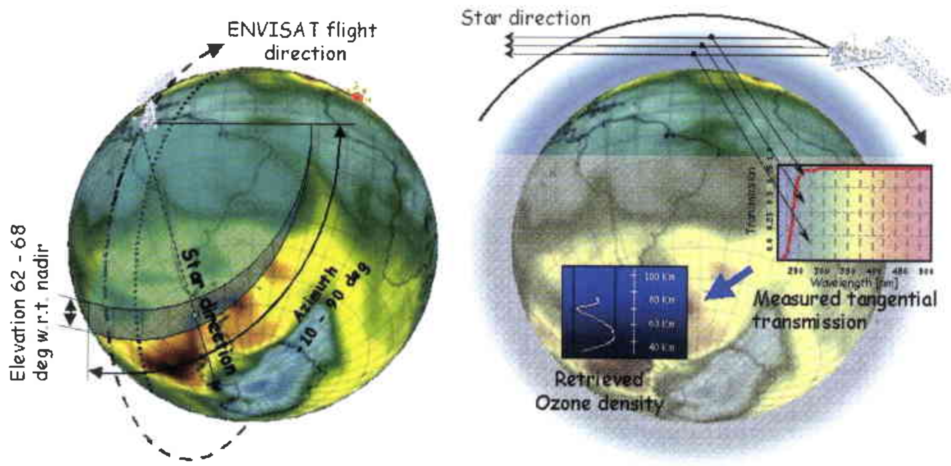


Figure 3. GOMOS viewing geometry and measurement principle. The left panel illustrates the instrument-pointing envelope (range of all possible pointing directions), whilst the right panel shows an occultation sequence. As the satellite moves away from the star, it will appear to fall behind the horizon. As the atmosphere occults the star, the acquired spectra will increasingly show absorption features (due to ozone and other gases)

of a target star, detected at tangent heights well above the atmosphere, and the occulted spectra as modified by the atmospheric absorption, obtained while the star sets behind the horizon. Using these transmission spectra and the known molecular cross-sections, the vertical trace-gas profiles are retrieved.

The primary goal of GOMOS is the accurate detection of stratospheric ozone, allowing one to monitor global trends in this species over long periods. Whilst providing ozone profiles from UV-visible occultation spectra in an altitude range of ~15 – 80 km and with a vertical resolution of better than 1.7 km, the instrument will yield small-scale turbulence measurements and high-resolution temperature profiles using two fast broadband photometers in the visible spectrum.

The instrument's line-of-sight (LOS) can be pointed over a large contiguous range, reaching from the anti-flight direction to the across-track direction (Fig. 3). It is controlled by a steering front mirror, allowing the LOS to be pointed in azimuth from -10 to 90 deg (w.r.t. the anti-flight direction), and in elevation from 68 down to 62 deg (w.r.t. nadir direction).

Initially the mirror is controlled in open loop to a fixed pre-programmed position. Once the star is detected, it is controlled in closed loop via the star tracker (Fig. 4). The observation of a particular sequence of star occultations requires the uploading of a set of star parameters that control the initial pointing direction and the apparent angular velocity (due to the satellite's motion) of individual target stars. The selection of the stars and the optimisation of the overall measurement sequence are performed on the ground for a series of orbits, and take into account the various scientific objectives. The target objects are selected from a catalogue containing about 1000 stars down to magnitude 4.5, ensuring global occultation measurement coverage throughout the year (Fig. 5).

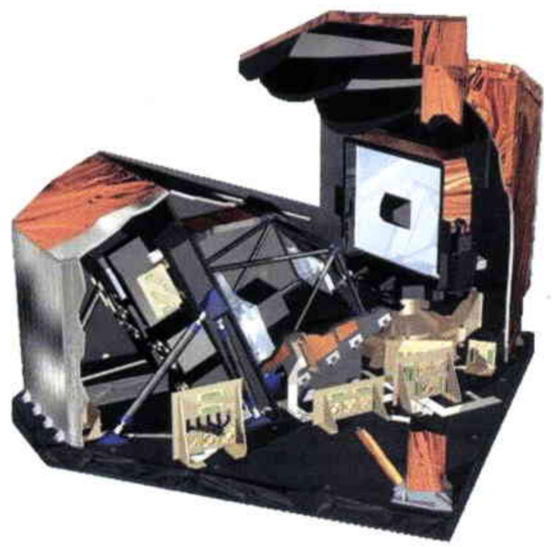
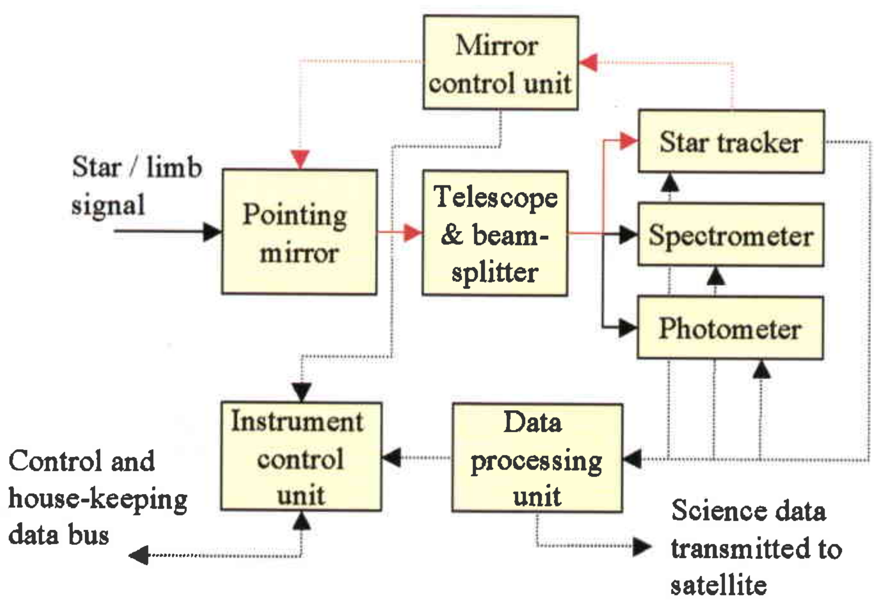


Figure 4. The GOMOS instrument (artist's view) and its functional breakdown



During the occultation, a star will appear to move in a downward and slightly lateral direction. This effect is compensated for by the fine-pointing mechanism mounted on top of the coarse pointing mechanism, which is used only for the initial acquisition of the star. In addition, the fine-pointing control loop corrects for short-term perturbations induced by both refraction and scintillation effects.

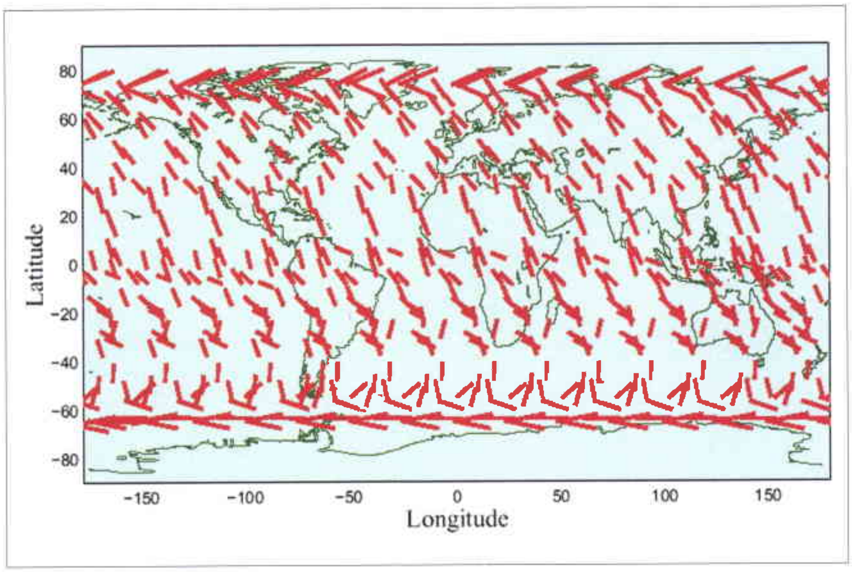


Figure 5. Typical GOMOS coverage during one day in March. The map indicates the geo-location of limb tangent points during the acquisition of a realistic sequence of star occultations (courtesy of FMI, Finland)

Towards the end of an occultation sequence, the starlight eventually becomes so attenuated that the instrument can no longer observe and track the star. The star is finally lost behind the horizon and the instrument changes its pointing direction (i.e. points the mirror) to the next star on the observation list. In this manner, the instrument will typically acquire 45 stars per orbit, yielding a total of 178 000 occultations per year.

In summary, with a star-parameter table loaded, the instrument will operate fully autonomously for up to 25 orbits before a new star table has to be uploaded.

A schematic of the instrument and its primary functional components is provided in Figure 4, whilst Table 1 lists the basic instrument characteristics.

Table 1. Basic characteristics of the instruments

Performance parameter	Value (Dark limb)
Spectrometer spectral range [nm]	UV : 250 - 375, VIS : 405 - 675, IR1 : 756 - 773, IR2 : 926 - 952
Spectrometer spectral sampling [nm per pixel]	UV : 0.314, VIS : 0.314 IR1 : 0.0465, IR2 : 0.057
Spectrometer spectral resolution [nm] (FWHM of line spread function)	UV : 0.89, VIS : 0.89 IR1 : 0.12, IR2 : 0.14
Spectral stability knowledge [nm]	UV : 0.04, VIS : 0.04 IR1 : 0.007, IR2 : 0.008
Spectrometer integration time [Sec]	0.5
Photometer spectral range [nm]	Blue : 470 - 520, Red : 650 - 700
Photometer integration time [sec]	0.001
Star tracking visual magnitude limit : Blue star = 30,000K Red star = 3000 K	Blue : 4.64 Red : 6.81

GOMOS is inherently a self-calibrating instrument. This means that long-term drifts in the instrument's radiometric response are compensated for as only the ratios of measurements, acquired over a relatively short time interval (~40 s), are used to compute transmission spectra. Changes in instrument response are negligible over such short intervals. Although GOMOS is specifically optimised for night observations, it will also perform measurements during daytime (bright-limb conditions). During daylight measurements, the bright background limb spectrum needs to be removed from the star spectra, via the simultaneous measurement of the pure limb signal just above and below the star LOS. The interpolated limb spectrum is then subtracted from the star band.

Ground processing

The geophysical products of GOMOS are vertical density profiles of ozone, O_2, NO_2, NO_3, H_2O, OClO, air and aerosol extinction. They are retrieved from the horizontal transmission spectra via a spectral inversion followed by a vertical inversion (Fig. 6). In addition, high-resolution temperature profiles are retrieved.

- *Level-1B data processing (pre-processing)*

The main objectives of this processing stage are:
- measurement-data quality control
- correction for instrument effects
- geo-location of tangent point due to refraction effects ('bending' of LOS)
- computation of atmospheric-transmission and limb-background spectra.

Prior to the retrieval of geophysical parameters, a number of corrections are applied to the absorption spectra during the Level-1B processing stage. These corrections primarily account for non-uniformity of detector sensitivity and wavelength shifts due to residual pointing errors. Additional steps include the verification (internal consistency check) of observational data, the computation of geo-location parameters and various radiometric corrections (detector-uniformity effects and stray-light removal). The final step includes the subtraction of a background signal and the generation of transmission spectra.

The photometer computations are achieved using a similar processing chain.

- *Level-2 processing (geophysical-product generation)*

The Level-2 processing stage comprises the retrieval of trace-gas abundances, aerosol

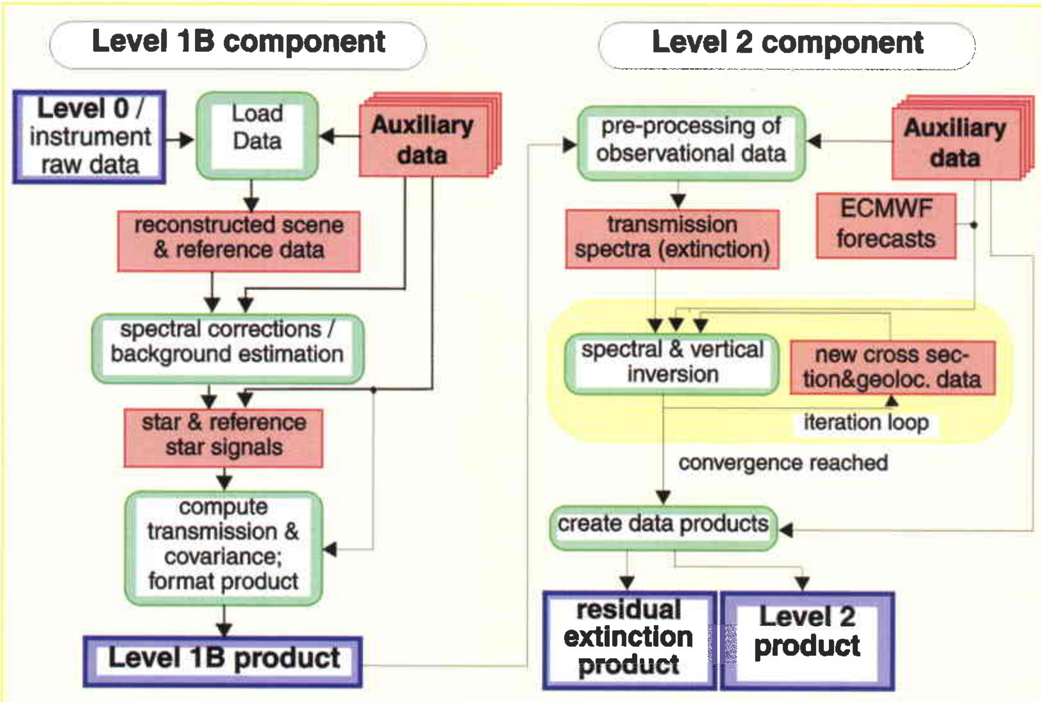


Figure 6. The GOMOS ground-processing chain

extinction parameters including wavelength dependence, air density and temperature profiles. The major processing steps are:

- retrieval of processing configuration data, instrument physical characteristics, Level-1B products and cross-section information
- correction of transmission spectra for scintillation effects and dilution.
- chromatic refraction correction (if necessary)
- spectral and vertical inversion
- product formatting.

MIPAS

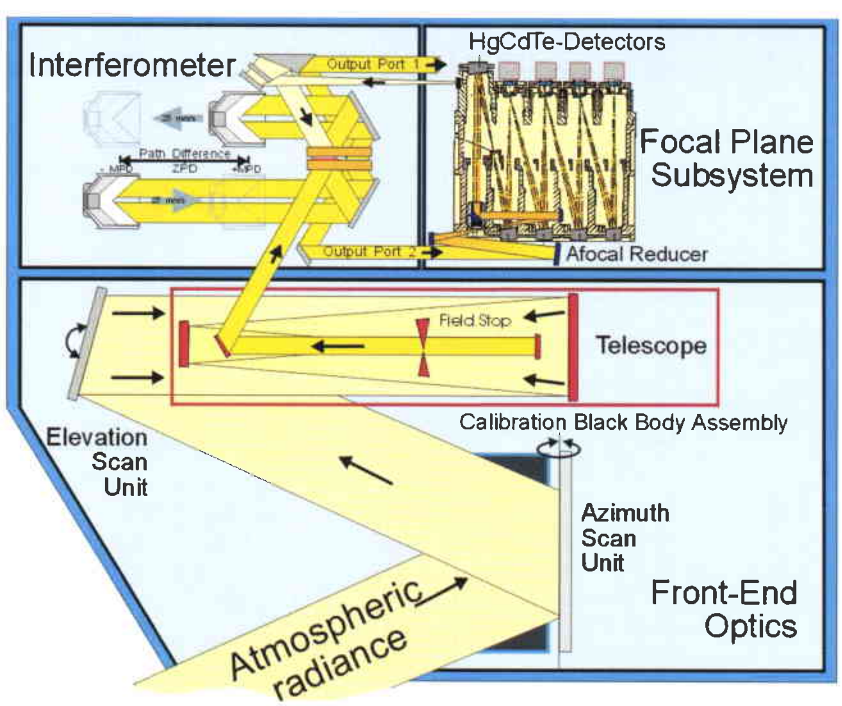
The MIPAS instrument has been designed to acquire global measurements of the Earth's limb emission, ranging from the upper troposphere to the mesosphere. Analysis of numerous trace gases exhibiting spectral features in the 685 – 2410 cm^{-1} wave-number interval (14.6 – 4.15 micron wavelengths) is envisaged, with a focus on stratospheric ozone chemistry and dynamics. In particular, MIPAS will provide global observations of NO_y compounds and of all important greenhouse gases. Moreover, it will allow the sensing of various species in the upper troposphere and in the mesosphere. Such measurements are relevant for studies of tropospheric chemistry, tropospheric/stratospheric exchange processes, and the Earth's global energy budgets.

Instrument design

The scientific objectives of MIPAS impose a number of challenging requirements in terms of radiometric sensitivity, spectral resolution and pointing stability. The concept finally selected is based on a dual-slide interferometer in conjunction with an anamorphotic telescope at the instrument's input and a set of eight Hg:Cd:Te detectors located at the two output ports of the interferometer. A schematic of the instrument's optical layout is shown in Figure 7.

The atmospheric radiance enters the front-end optics through the azimuth and elevation scan mirrors, which allow one to control the instrument's line-of-sight (LOS) in the horizontal and vertical viewing directions, respectively. The azimuth scan unit also allows switching of the viewing direction between sideways (orthogonal to the orbit plane, 'anti-Sun' direction) and rearward ('anti-flight' direction) geometries, and to view the internal blackbody target for periodic radiometric calibration. The

Figure 7. The MIPAS optical design (schematic)



elevation scan unit controls the LOS viewing direction according to pre-defined tangent altitudes, and also the pointing to high altitudes (~200 km) required for radiometric offset correction ('deep-space' calibration).

The elevation scan mirror reflects the input scene into the telescope, which reduces the beam size by a factor of 6 in azimuth, with no reduction in the elevation direction. An aperture stop located near the intermediate focus defines the effective overall field-of-view (FOV) of the instrument, which is 0.9 mrad in elevation by 9 mrad in azimuth. Primary components of the interferometer are the beam-splitter assembly, two corner-cube reflectors mounted on linearly moving slides, and the optical-path-difference sensor (ODS). The latter provides information on the actual optical path difference during the acquisition of interferograms, and controls the discrete sampling of the detector output signals.

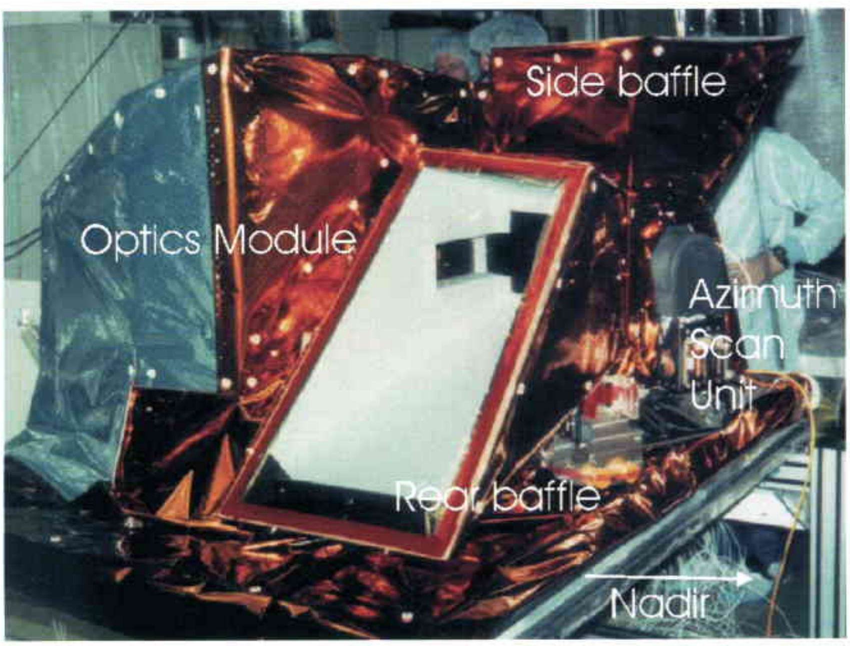


Figure 8. The MIPAS optics module, with the side and rearward (front) baffles removed

A major driver for the overall instrument design is the achievable spectral resolution, which is directly related to the maximum optical-path difference (MPD) of a two-beam interferometer. The required resolution for MIPAS is 0.035 cm^{-1}, which translates into an MPD of 20 cm, taking into account various effects that result in a degradation of resolution, such as internal misalignment, beam divergence and the finite field-of-view. The actual mechanical excursion of each reflector slide is ± 5 cm, taking into account the doubling of the optical path due to reflection and the opposite direction's of the slides' movements. Various additional optical elements, primarily folding mirrors, have been included in the optical path, in order to reduce the overall size of the instrument. An impression of the instrument's dimensions is provided in Figure 8, which shows the optics module, with the two baffles for the rearward and sideways viewing geometries clearly visible.

The chosen interferometer design provides two separate input and output ports. While one input port is fed by the signal from the input telescope, the second port is terminated by a cold absorber. The two output ports are directed to two sets of four detectors, each set covering the entire spectral range of MIPAS. This set-up allows the radiometric performance to be enhanced through the co-addition of spectrally overlapping channels, and provides redundancy in the event that one or more detectors experience performance degradation or failure during in-flight operation. The detectors, together with their fore-optics (lenses, dichroics), are mounted in a common housing that is cooled to 70 K by means of a pair of Stirling-cycle coolers, in order to achieve optimum sensitivity and to reduce excessive noise due to thermal emissions in the input-signal path.

During the acquisition of interferograms, the signals of all eight detectors are individually amplified and digitised, using the sampling signal generated by the ODS. Subsequently, digital post-processing is performed for the individual detector channels in order to reduce the overall data rate. A total of six interferograms covering different spectral regions are finally generated for each interferometer stroke and formatted into a sequence of data units (source packets). These source packets also include various supplementary parameters and housekeeping information, required for the correct interpretation of the measured data on the ground.

A number of control and monitoring functions are required during the operation of MIPAS. These tasks, as well as the communications between the instrument, the Envisat platform and the control station on the ground (Flight Operations Segment, FOS), are handled by the Instrument Control Unit.

A simplified overview of the primary components of MIPAS is given in Figure 9, and the requirements and primary performance parameters are summarised in Table 2.

Observational strategy
MIPAS will periodically acquire atmospheric-limb emission spectra by scanning the instrument's line-of-sight (LOS) elevation in discrete steps, to cover a typical tangent height range of 8 to 68 km. At the beginning of each elevation scan, the azimuth angle is adjusted

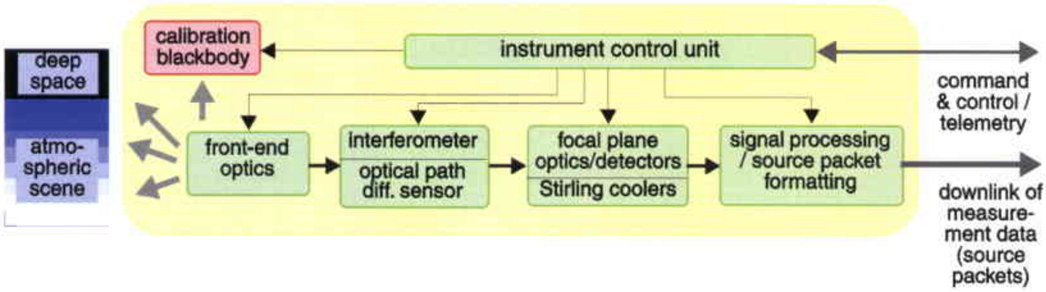


Figure 9. Schematic of MIPAS primary functional components

in a ±15 deg range around the nominal (rearward) direction, to compensate for the orbit's inclination (98.55 deg) and to view the polar areas (Fig. 10).

A single interferometer stroke is performed at each altitude while interferograms are recorded in the 8 detector channels (A1, A2, ..., D1, D2). Assuming 16 tangent heights per elevation scan, a measurement time of 4.45 s per stroke (high resolution, MPD = 20 cm), and taking into account periodic radiometric deep-space calibrations, about 75 complete scans will be acquired during each orbit (period = 100.6 min). The average data rate will be approx. 420 kbit/s.

Ground processing

The MIPAS ground-processing chain is composed of a Level-1B and a Level-2 component, which can be operated either in sequence or as independent stages. The Level-1B stage performs the conversion of instrument raw data (scene, blackbody and deep space) and auxiliary data into radiometrically and spectrally calibrated, geo-located radiance spectra. Also, a number of supplementary parameters are computed, which are required for the correct interpretation of the Level-1B data. The following functionalities are provided:

Pre-processing functions
- Extraction and reconstruction of interferogram data (scene and calibration data) from a Level-0 input product.
- Extraction/processing of additional ('auxiliary') input data and instrument housekeeping information (e.g. timing/pointing data, health status information).

Main processing functions
- Correction of detector non-linearity (for long-wavelength – band A, AB, B – detectors).
- Channel equalisation and combination (band-A detectors).
- Detection/correction of spurious signals ('spikes') and of possible ODS sampling ('fringe count') errors.
- Processing of radiometric gain and offset calibration data.
- Radiometric calibration of scene data, and correction of spectral-axis assignment (spectral calibration).
- Computation of geo-location parameters (for individual sweeps for elevation scans, refraction corrected).
- Assessment/verification of scene quality and noise equivalent spectral radiance (NESR).

Table 2. MIPAS performance summary

Observation Geometry	
Field of view at limb tangent point	**3 km (vertical) x 30 km (horizontal)**
line of sight viewing range	**vertical: 5 ... 200 km (tangent height)** **horizontal: 35^0 about rearward (anti-flight) direction** **30^0 for sideways viewing geometries (specialL events monitoring only)**
Spectral Sampling	
total spectral range	**685 ... 2410 cm^{-1} (λ = 14.6 ... 4.15 μm)**
spectral bands	**A: 685 - 970 cm^{-1}, AB: 1020 - 1170 cm^{-1}, B: 1215 - 1500 cm^{-1}, C: 1570 - 1750 cm^{-1}, D: 1820 - 2410 cm^{-1}**
spectral resolution (unapodised)	**~ 0.03 cm^{-1} (high resolution, MPD = 20 cm)** **~ 0.25 cm^{-1} (low res., MPD = 2 cm)**
Radiometric Performance	
noise equivalent spectral radiance, NESR ('sensitivity')	**50 $nW/cm^2/sr/cm^{-1}$ (band A) ... 4.2 $nW/cm^2/sr/cm^{-1}$ (band D)**
radiometric accuracy	**1 % (@ 685 cm^{-1}) ... 3 % (@ 2410 cm^{-1}) of input spectral radiance**
Spatial Sampling	
total number of elevation scans per orbit (nominal mode)	**~ 80 (high resolution, 16 limb heights per scan)**
along-track spacing between scans	**500 km**
ground track of LOS tangetn point	**almost polar (compensation of orbit inclination through azimuth steering)**

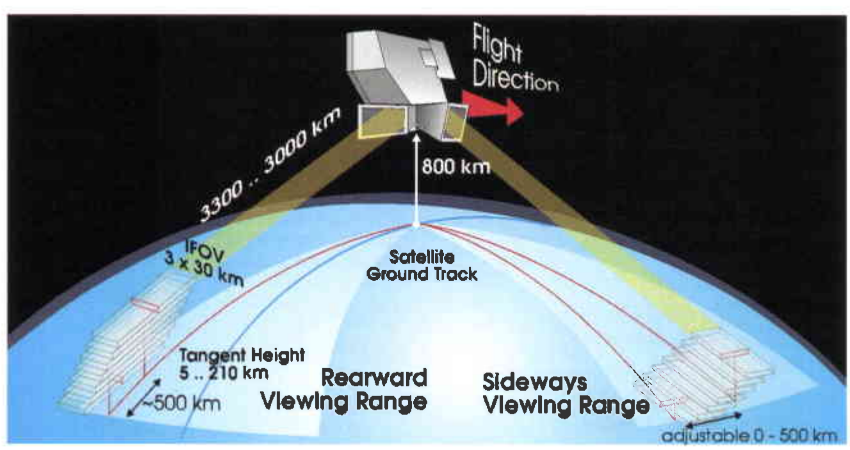


Figure 10. MIPAS line-of-sight viewing geometry

In a final step, a number of additional annotation data are generated and formatted, together with the calibrated limb-radiance data in a Level-1B product.

The Level-2 processing is based on the analysis of emission features of selected target gases from the Level-1B input data and is performed in two stages: (i) retrieval of pressure/temperature profiles, and (ii) sequential retrieval of Volume Mixing Ratio (VMR) profiles for the target species O_3, H_2O, CH_4, N_2O, NO_2 and HNO_3, using the pressure and temperature information retrieved in the first stage.

The underlying retrieval concept is derived from the so-called 'global-fit technique'. This approach corresponds to the simultaneous analysis of the full set of available observations (i.e. Level-1B radiances at different limb altitudes within a given scan) and minimising the CHI_2 function, i.e. the weighted summation of quadratic differences between observations and simulated signals. This minimisation represents a non-linear problem and is achieved through simultaneous fitting of all selected unknowns, i.e. primarily the parameter profiles of an initially assumed model atmosphere. (More details on the mathematical background of the iterative fitting procedure and the atmospheric model can be found in the MIPAS Science Report, ESA Special Publication SP-1229).

A simplified overview of the Level-1B/2 processor stages is given in Figure 11.

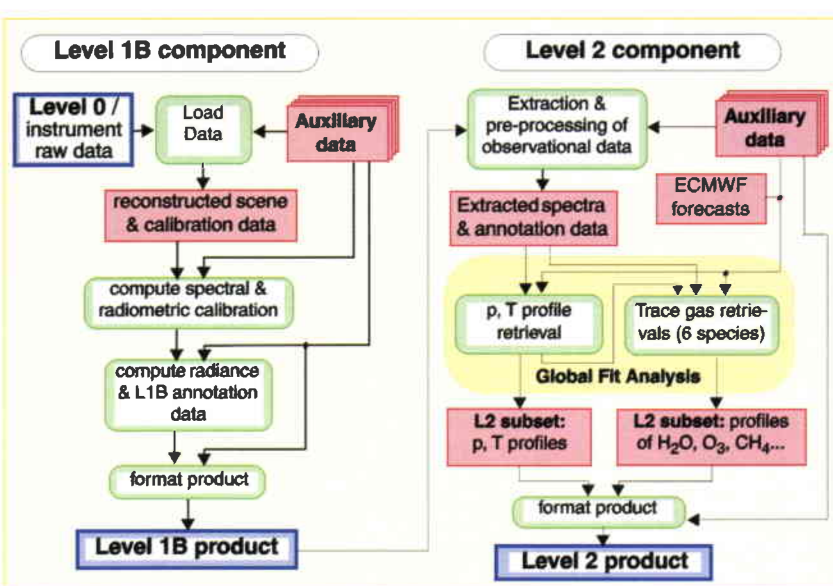


Figure 11. The MIPAS ground-processing chain

SCIAMACHY

Instrument design

The Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) will measure the sunlight and moonlight that is either transmitted, reflected or scattered by the Earth's atmosphere. The double spectrometer is designed for the ultraviolet, visible and near-infrared wavelength domains (240 – 2380 nm), covering this range with a resolution of 0.24 to 1.5 nm. It was conceived to improve our knowledge and understanding of a variety of important issues relating to the chemistry and physics of the Earth's atmosphere: troposphere, stratosphere and mesosphere. The scientific objectives are to study stratospheric chemistry, troposphere-stratosphere exchange processes and tropospheric pollution, by using a combined limb, nadir and occultation strategy.

SCIAMACHY is a passive remote-sensing instrument, designed to measure atmospheric constituents and parameters of importance in the stratosphere and troposphere. It comprises four subsystems:
- A scan-mirror system, which determines the instrument's observational mode.
- A spectrometer (or optical bench), which breaks down the incoming signal into its spectral components
- A cooling system, which maintains the spectrometer and its detectors at selected temperatures to optimise the signal-to-noise ratio in the measured spectra.
- An electrical subsystem, which controls and operates SCIAMACHY and interfaces to the Envisat platform.

The first two subsystems are partly depicted in Figure 12. The input light is collected by the scan-mirror system and passed, via an off-axis parabolic mirror, to the spectrometer's entrance slit. After subsequent collimation, light is directed to a pre-dispersing prism, which produces an intermediate spectrum in the middle of the instrument (see Fig. 12, where the prism is labelled the 'channel separator'). The polarised reflection of this prism is sent to the Polarisation Measurement Devices (PMDs), which are broadband detectors observing in selected ranges throughout the spectral range of SCIAMACHY. The spectrum leaving the prism is directed, by use of reflective optics and dichroic mirrors, to the eight spectral channels of SCIAMACHY. Each channel comprises a grating, transmissive optics and a diode array detector. The optical bench and its array detectors are cooled to minimise their intrinsic noise, and thereby optimise the signal-to-noise ratio.

The onboard calibration hardware includes aluminium diffusers (on the rear sides of the elevation and azimuth scan mirrors), which are used for solar-irradiance measurements. These in turn are used to calibrate Earth-shine spectra, for use in ground processing. A hollow cathode discharge lamp is used for wavelength calibration. The detector pixel-to-pixel gain, as well as etalon effects, will be determined using a tungsten-halogen 5 W lamp, placed at the second level.

With its combination of two mirrors, the instrument is able to observe light reflected, scattered or transmitted from the atmosphere, in nadir, limb or occultation mode. It yields either trace-gas column densities from nadir measurements, or vertical profiles from limb and occultation measurements. In combination with the instrument's broad spectral coverage, this leads to a unique quantity of scientific targets and applications. Especially the combined analysis of limb and nadir measurements will make SCIAMACHY the only instrument on Envisat that can estimate tropospheric trace-gas columns (Fig. 13). In the future, these might be of considerable interest for tropospheric ozone detection and photo smog monitoring.

Observational strategy
The SCIAMACHY operations concept is built on a mission scenario – timeline – state scenario. The lowest level, an instrument state, represents a single measurement type with a specific set of (pre-)defined parameters. Several of the instrument states together build a timeline, defining a sequence of measurements. Both, states and timelines are stored on-board the satellite. Commanding these pre-defined timelines will allow autonomous instrument operation over long periods. Mission scenarios define the high-level sequence of activities.

Nominally, SCIAMACHY will be operated as follows. Coming out of eclipse, the instrument will start with occultation measurements by tracking the sunrise through the atmosphere. Alternating limb and nadir measurements will follow, performed with a nominal swath width of 960 km across-track. Whenever the Moon is visible (which occurs over the southern hemisphere of the day-side orbit), lunar occultation will be performed. Calibration measurements will be carried out when entering eclipse

Given Envisat's orbital period of about 100 minutes, SCIAMACHY will be able to observe the whole Earth. Global coverage at the equator is established within 6 days when using the alternating limb/nadir scan option. Using only the nadir or limb modes, global coverage is achieved within 3 days (for the 960 km swath width).

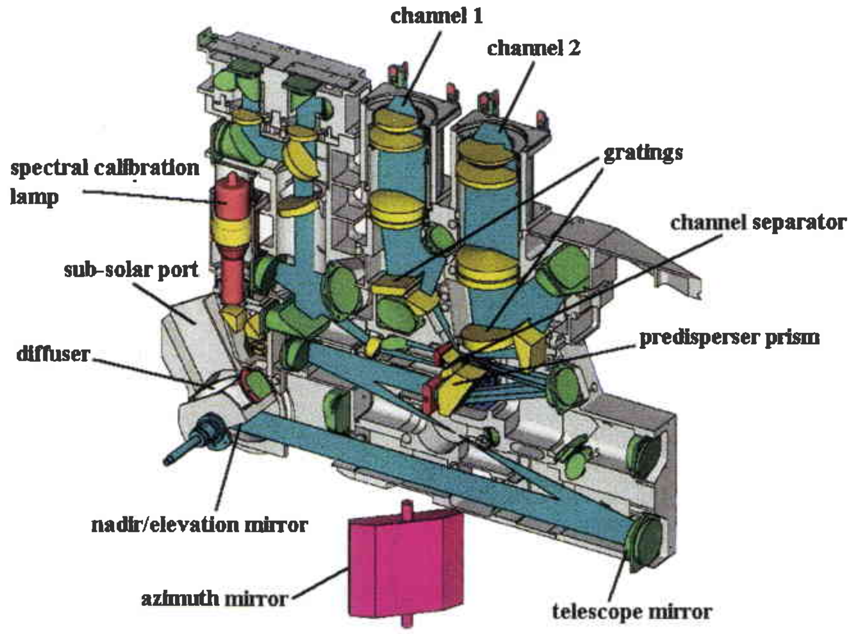


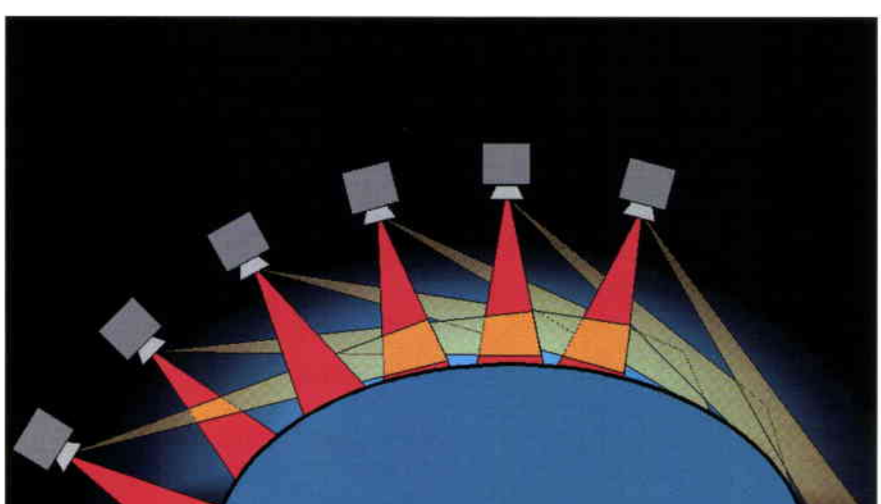
Figure 12. The SCIAMACHY level-1 optics. The second level (not shown here) consists of the remaining channels 3 to 6, PMD channels including a 45 deg sensor, and the on-board white-light source (courtesy of TPD/TNO, The Netherlands)

Ground processing
SCIAMACHY Level-1B processing comprises the following steps:

- Reading of Level-0 (raw) data and auxiliary files.
- Sorting data packets according to nadir, limb/occultation, calibration and monitoring categories.
- Determination of measurement data geo-location.
- Determination of calibration/correction parameters necessary for spectral and radiometric calibration.
- Write Level-1B product, containing the geo-located measurement data (still Level-0), plus all calibration/correction parameters.

The SCIAMACHY Level-1B product concept differs from the standard approach adopted for the other Envisat instruments in so far as a user has to apply various corrections and calibrations in order to obtain fully calibrated, geo-located radiance spectra. This rather specific interpretation of Level-1B is based on the ERS-2/GOME heritage. By maintaining the

Figure 13. SCIAMACHY limb/nadir matching. By assessing the difference between nadir total column and limb integrated stratospheric column, the tropospheric column can be obtained (courtesy of IUP, Bremen)



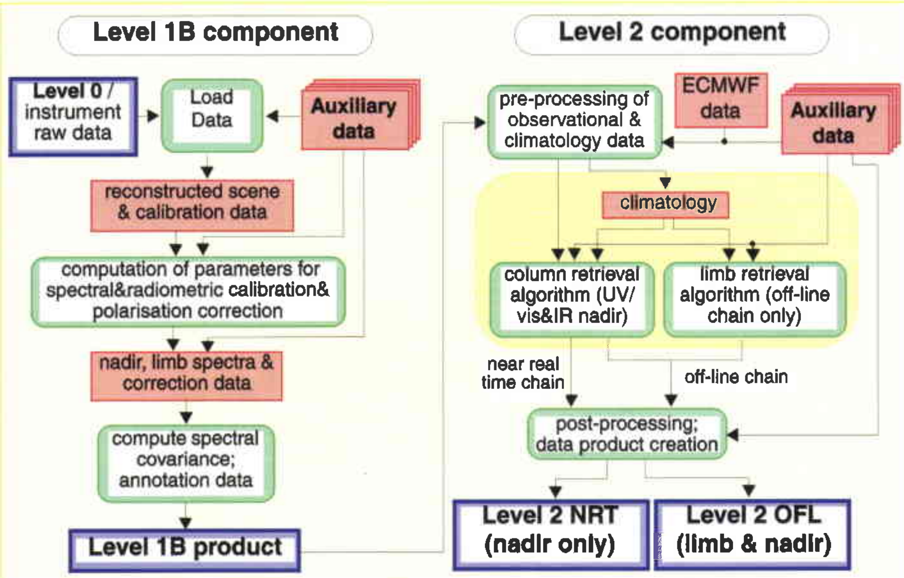


Figure 14. The SCIAMACHY ground-processing chain

'raw' information content in the Level-1B product, it provides the users with a high degree of flexibility to perform calibrations according to their specific needs.

Taking Level-1B as input, Level-2 processing involves the following steps:
- Reading Level-1B data and auxiliary data (e.g. climatology, cross-section data).
- Applying calibrations for: leakage current, detector memory effect, etalon and pixel-to-pixel gain, stray light, spectral, polarisation and radiance.
- In NRT processing, only nadir data will be processed with DOAS-type (Differential Optical Absorption Spectroscopy) algorithms to retrieve vertical columns of trace gas.
- In off-line processing, nadir, limb and occultation data will be processed, to yield vertical profiles of trace gases.
- Finally, retrieval results are written into the Level-2 product.

A simplified overview of the Level-1B/2 processor stages is given in Figure 14.

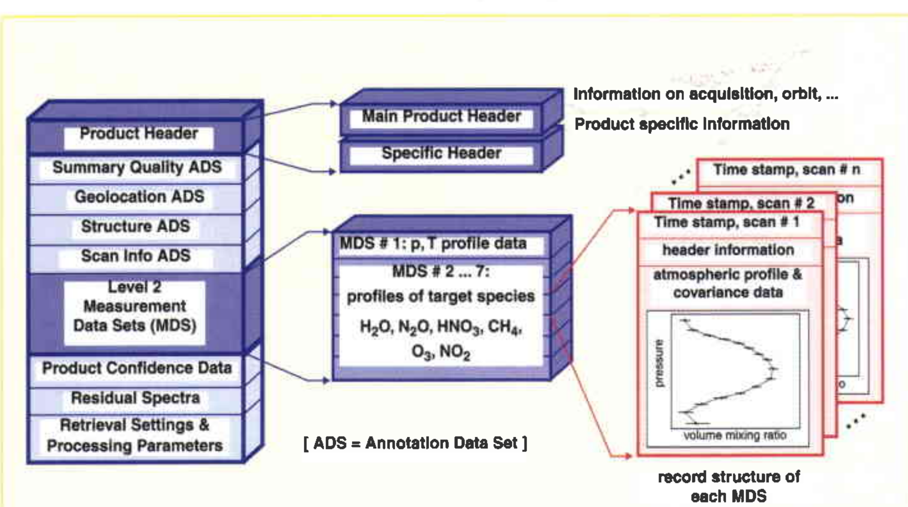


Figure 15. Structure of a MIPAS Level-2 product file

Scientific data products

During Envisat's routine operations, GOMOS, MIPAS and SCIAMACHY will acquire atmospheric data according to a nominal measurement scenario. These data will be interleaved with periodic, instrument-specific calibration and characterisation measurements, as required to perform the ground data processing and to monitor the performance of each instrument. The processing of scene and calibration data for each of the instruments will be conducted on a systematic basis, making use of the near-real-time (NRT) and off-line processing capabilities provided by the Payload Data Handling Stations (PDHS) and Processing Archiving Centres (PACs), respectively (see the 'Payload Data Segment' and 'Envisat User Services' articles elsewhere in this issue).

All product files are structured according to the general Envisat formatting rules that distinguish the following 'generic' building blocks:
- *Main/Specific Product Header (MPH/SPH)*: Product header, specifying both general and instrument-related information such as processing site, software version, orbit/geo-location parameters, sensing time, and references to auxiliary input data used.
- *Measurement Data Sets (MDS)*: Include actual processed instrument data, i.e. transmission/emission spectra in the case of Level-1B products and retrieved geophysical parameters (profile or column density data), in the case of Level-2 products.
- *Annotation Data Sets (ADS)*: Include MDS-specific information related to acquisition or processing of individual data segments, as required for full interpretation of the data.

Whereas in the case of GOMOS each individual occultation results in a set of Level-1B and Level-2 files, the MIPAS and SCIAMACHY products contain data for a full orbit. In the latter case, the MDS are formatted according to a specific record structure, whereas each record corresponds to an individual processed measurement data unit, for instance a limb sequence. The records within each data set can be identified by a unique time parameter, the so-called 'time stamp'. A typical product file structure (MIPAS Level-2) is illustrated in Figure 15. ESA will provide the users with specific software tools to support the handling of product files and the extraction of geophysical information.

Table 3. Envisat's atmospheric data products

Instrument		GOMOS	MIPAS	SCIAMACHY	
Level 0		raw instrument data, time ordered, header and quality information			
Data volume [a]		40 Mbytes	290 Mbytes	320 Mbytes	
Level 1 B		calibrated transmission & background spectra	calibrated limb emission spectra	engineering corrected limb, nadir & occultation spectra	
Data volume [a]		250 Mbytes	310 Mbytes	180 Mbytes	
Meas. Geometry		Limb	Limb	Nadir	Limb
Level 2 routine products	NRT	profiles of T, O_3, NO_2, NO_3, H_2O, O_2, air density, aerosols	profiles of p, T, O_3, H_2O, CH_4, N_2O, HNO_3, NO_2	O_3, NO_2, H_2O, CO, CH_4, N_2O, clouds, aerosols [SO_2, OClO, H_2CO] [b]	-/-
	Off-Line	same as NRT	same as NRT	same as NRT + BrO, SO_2, CO_2, p, T	O_3, NO_2, BrO, H_2O, CO, N_2O, CH_4, aerosols, p, T
Data volume [a]		70 Mbytes	9 Mbytes	5 Mbytes	?
Additional retrievable quantities		[BrO, OClO] [b]	NO, N_2O_5, $ClONO_2$, HNO_4, CO, CFCs, CCl_4, CF_4, C_2H_2, C_2H_6, PSC's, aerosols, cloud data	profiles of O_3, H_2O, CO, N_2O, CH_4, CO_2	p, T, O_3, NO_2, CO_2, BrO, H_2O, CO, N_2O, NO_2, CH_4 profiles from occultation soundings

a. Typical figure, per orbit
b. observable under specific conditions (enhanced abundancies) or after averaging

A summary of the data products for the three instruments is provided in Table 3. In addition to the routine products that will be systematically processed in the various processing centres, a number of 'non-standard' target species/ parameters are listed (bottom row of table). These products will require enhanced analysis strategies and are the subject of dedicated research efforts in a number of scientific research institutes located all over Europe.

In-flight characterisation and validation

During Envisat's early in-orbit operation, its atmospheric sensors will undergo a number of checks and calibration measurements to verify the basic functionalities of the instruments and ground-processor components, and to assess essential performance parameters. Primary contributions to the validation of atmospheric products will be supplied by dedicated measurement campaigns providing independent observations of atmospheric parameters. Advantage is taken of a variety of well-proven measurement techniques, including various ground-based, airborne and space experiments.

Intercomparisons of GOMOS, MIPAS and SCIAMACHY data with such 'correlative' information will allow error budgets for the geophysical data products to be quantified and corrective actions to be identified in order to further enhance the overall performance of the ground processing chains.

The initial in-flight calibration/characterisation activities will be accompanied by dedicated geophysical measurements. These efforts will be complemented by a long-term validation programme ensuring continuous performance monitoring of the instruments and ground processors, and allowing the incorporation of future enhancements for critical algorithm components.

Conclusions

With the GOMOS, MIPAS and SCIAMACHY instruments onboard Envisat, ESA's series of Earth-observation missions will be enriched with a suit of powerful sensors dedicated to the exploration of the entire lower and middle atmosphere. Whilst operating in different spectral bands spanning the ultraviolet to mid-infrared wavelength range, the three instruments will exploit a variety of detection techniques and observational strategies. Together, they will provide global data on a large variety of atmospheric-state parameters, primarily abundancy profiles for the trace gases that play a key role in understanding the atmosphere's chemistry and physics and which may contribute to the further improvement of meteorological forecasting models.

The concept of systematic processing, archiving and dissemination of scientific data products will ensure that the atmospheric research community is supplied with immediate and easy access to a large number of geophysical data products throughout Envisat's envisaged 5-year lifetime.

A co-ordinated validation programme including dedicated correlative measurement campaigns has been initiated to support both the initial and the subsequent routine in-orbit operation of the three instruments. This effort will ensure stable sensor and ground-processor performances throughout the entire lifetime, further improving the scientific exploitation possibilities for this unique atmospheric mission.

The Flight Operations Segment

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The Envisat Flight Operations Segment (FOS) provides the services needed to operate the Envisat platform and its instruments during the Launch and Early Orbit Phase (LEOP), the Commissioning Phase and the Routine Phase of the mission. In developing the FOS, extensive use has been made of existing components already developed and tested for the ERS missions. The resulting FOS is a distributed system, with a widely variable configuration depending on the different mission phases for which it will be used.

Introduction

The FOS is one element in the overall ground segment and it consists of the Flight Operations Control Centre (FOCC), the Kiruna (S) and Svalbard (N) ground stations, and the Launch and Early Orbit Phase (LEOP) network. Its main task is to monitor and control the Envisat satellite during the LEOP, Commissioning and Routine Phases, for which it interfaces with the following elements of the Envisat system:

- the satellite, for telemetry, telecommanding and ranging via the Kiruna, Svalbard, Villafranca (E) and LEOP stations
- the Payload Data Segment (PDS), for mission planning and reporting
- the Artemis Mission Control Centre, for the reservation of communication slots
- the Announcement of Opportunity Instrument (AOI) providers, for instrument operations
- the industrial partners (e.g. satellite Prime Contractor), for support during both the critical and routine mission phases.

Given the crucial role of the FOS in the overall success of the mission, stringent requirements for system availability, real-time performance, recovery, traceablity and validation have been systematically applied to all FOS elements. In addition, a validation of the operational procedures for all mission phases has been performed during System Validation Tests and during the FOS Simulation campaign.

FOS architecture

The FOS basically consists of the ground stations and the Flight Operations Control Centre (Fig. 1). ESA's Kiruna-Salmijarvi (S) facility serves as the prime station, complemented by the Svalbard (Spitzbergen) station to provide coverage during those orbits not visible from Kiruna. During the LEOP, the ground-station network will be temporarily extended to nine stations.

The Flight Operations Control Centre (FOCC), located at ESOC in Darmstadt, Germany, has the following components:

- The Flight Control System (FCS), which includes:
  - the spacecraft telemetry and telecommand database
  - the telemetry and telecommand systems, which are based on the corresponding, well-proven ERS systems
  - the Spacecraft Performance and Evaluation (Speval) archive, which is the long-term archive for telemetry and telecommand history data (with a web interface)
  - the on-board software maintenance system, which controls all patch and dump activities and guarantees configuration control for each change made to the on-board software
  - the mission planning system, which is used to plan and generate the daily command schedules.
- The Flight Dynamics System, which maintains the orbit and controls the on-board AOCS system.
- The Simulator, which realistically simulates the satellite's behaviour.

The ground stations

FOS GS - LEOP

During the LEOP, the requisite wide coverage of the flight path is provided by a network of nine ground stations, belonging to ESA or other organisations providing their services through

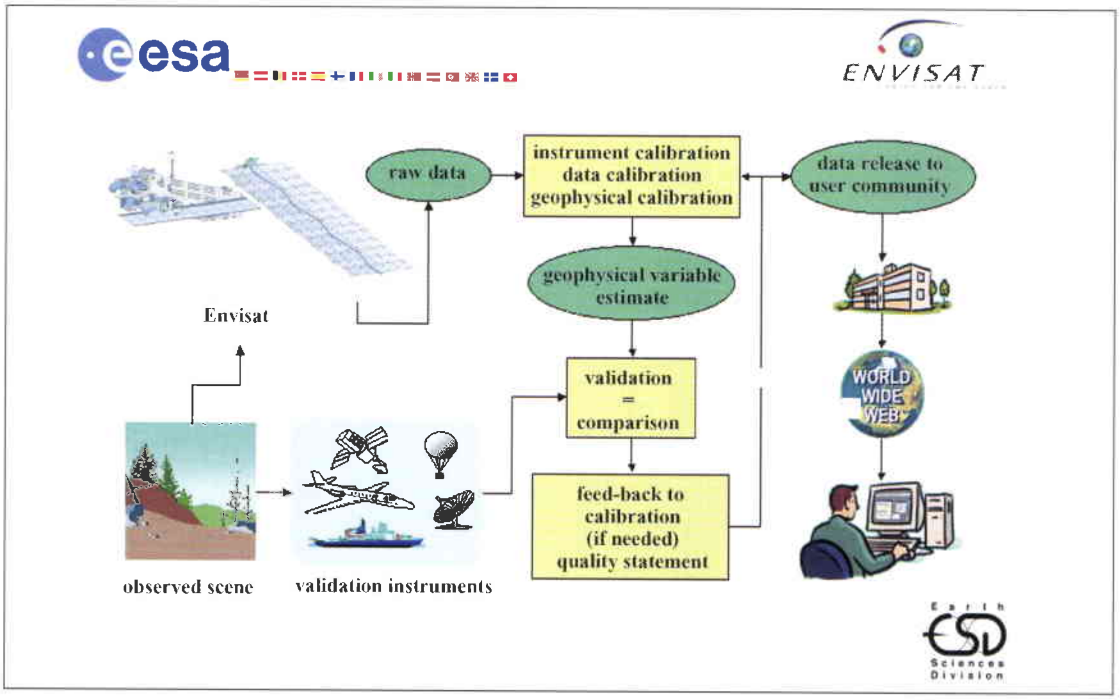

Figure 1. The structure of the Envisat Flight Operations Segment (FOS)

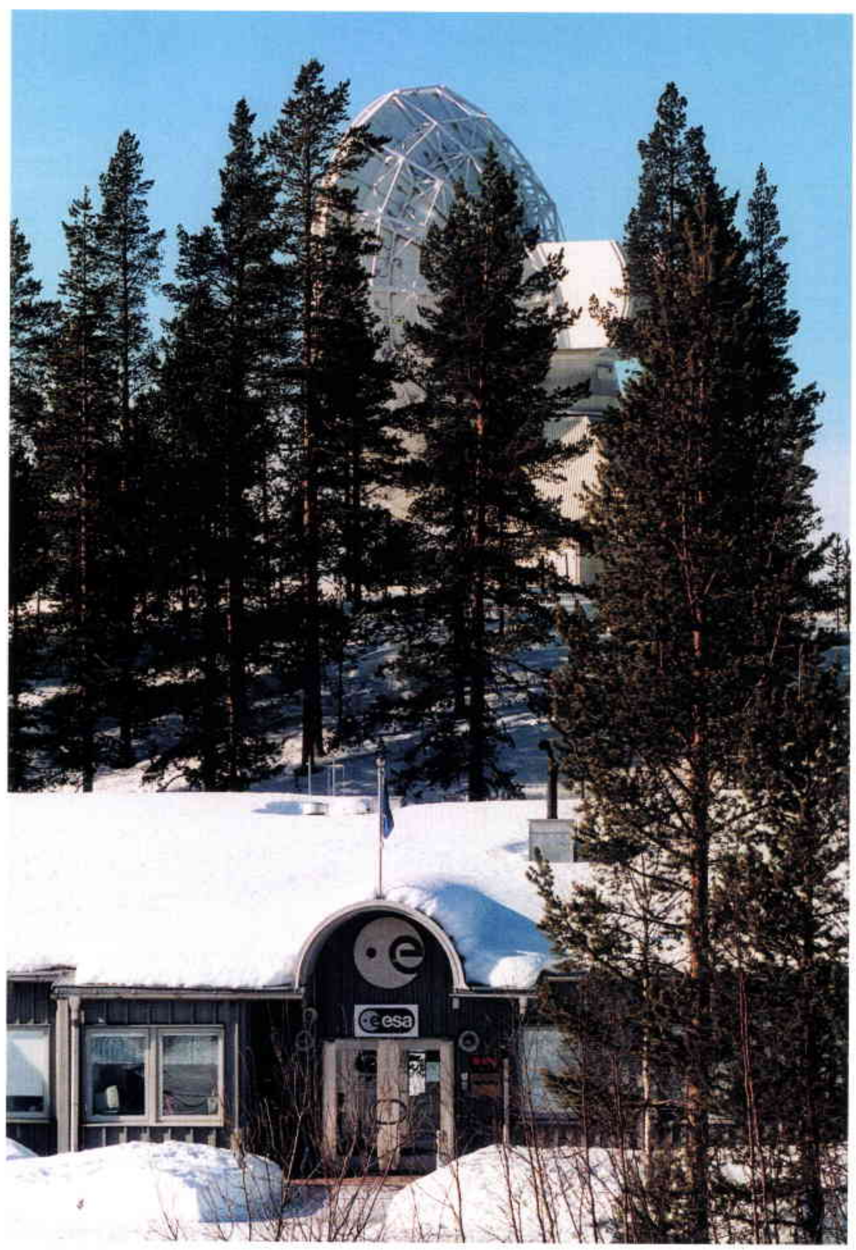

Figure 2. The Kiruna ground station, in Sweden

co-operation agreements. The LEOP ground-station network uses facilities at nine sites:
- Kourou
- Perth
- Villafranca
- Kiruna
- Santiago de Chile
- Wallops
- Poker Flat
- Kerguelen
- Svalbard.

The LEOP stations provide tracking, telemetry and command (TT&C) support in S-band. The ESA stations already being used for the Agency's missions did not require additional work in order to cope with Envisat. The non-ESA stations, although compatible at the radio-frequency level, have required some specific work at the base-band level (Santiago, Wallops and Poker Flat) or at the communications-link level (Kerguelen and Svalbard).

FOS GS - Routine

Monitoring and controlling the spacecraft during the Routine Phase of the mission relies on the ESA Kiruna-Salmijarvi (S) 15 m station as the prime station, complemented by the Svalbard station providing services during the Kiruna blind orbits. The ESA Villafranca (E) station will be used as the back-up during the Routine Phase.

The stations at Kiruna and Svalbard (Figs. 2 and 3) will provide full TT&C support in S-band when in direct visibility. The Kiruna-Salmijarvi station will also be used for the recovery of the housekeeping telemetry recorded by the on-board solid-state recorder over the whole orbit

Figure 3. The Svalbard ground station, in Norway

and dumped at X-band when within ground-station visibility. In order to support both the ERS and Envisat missions, an off-the-shelf 13 m antenna has been procured by the Swedish Space Corporation, the site operator, to provide S- and X-band services. Following Envisat's launch, the 15 m antenna's front-end will be re-furbished to support the next five years of Envisat operations.

During the initial phase of the Envisat mission, the Svalbard service will be provided by the station owned by Kongsberg Lockheed Martin, and operated by TSS. TSS is currently procuring another station to provide services at S- and X-band, to be operational at the beginning of 2002.

The above ground stations and the other FOS elements are connected via the ESA OPSNET network, which includes leased and dial-up lines via X.25 nodes. During the LEOP and Routine Phases, the OPSNET element will be operated centrally from ESOC. A network-control system allows remote control of each node in the network and switching of lines if needed.

The Flight Control System

The Envisat FCS provides the operators with facilities to both monitor and control the spacecraft. It includes database management (DB), telemetry processing (TM), telecommanding (TC), mission planning (MPS), on-board software maintenance (OBSM), local and remote spacecraft data-evaluation facilities (Speval, and via the web WebSpeval), monitoring and control of the Kiruna facilities (TTCDAF) and interfaces with the other elements of the Envisat ground segment. The FCS application software consists of the mission-specific software developed by industry, and the generic SCOS-1 infrastructure software. The SCOS-2000 infrastructure OBSM kernel supports the Envisat-specific OBSM subsystem.

The FCS is installed at ESOC in Darmstadt. The operational environment has been provided in the Envisat Dedicated Control Room (DCR) since the first SVT. During the LEOP, the Envisat FOCC will be installed in the Main Control Room (MCR).

The system hardware platform is set of three VAX computer systems connected in a protected Local Area Network. The user interface consists of up to 22 work stations, each with three screens. The system architecture supports all of the user requirements in terms of system availability and system response times, which are most severe for the critical mission phases, e.g. the LEOP. During these critical mission phases, a 'warm standby' is required, because it is not possible to restart a VAX computer system within the required one-minute time limit for system unavailability, whereas a 'cold standby' is sufficient for the mission's Routine Phase.

The Flight Control System consists of the following components:

- The database management (DB) provides the functionality for creating and managing the system databases. The Satellite Reference Database (SRDB) provided by industry is imported into a static Oracle database. The operational database used for real-time processing is derived from this static database and incorporated into the operational environment.
- The telemetry (TM) subsystem receives and processes the satellite telemetry. It receives real-time telemetry via X-25 links from the ground stations, or on-board-stored telemetry via a file interface from the Payload Data Segment (PDS). The telemetry subsystem quality-checks and processes all telemetry formats.
- The telecommand (TC) subsystem provides all of the features necessary to prepare, uplink and verify the commands. A history of all commands sent to the satellite is also maintained. Full manual operation of the spacecraft is supported. In normal operation modes, however, this system will uplink parameters and commands received from internal or external sources.
- The Mission Planning System (MPS) is part of the Envisat end-to-end planning function responsible for the planning and scheduling of the satellite and ground facilities. Its main task is to plan the spacecraft operations, according to requests for operations as

defined in the Reference Operation Plan (ROP) and in the Preferred Exploitation Plan (PEP). This activity must be conducted within the framework of satellite and ground constraints and in co-ordination with the Artemis satellite ground-segment planning function. The MPS provides the satellite, the ground-station schedule and the Detailed Mission Operation Plan (DMOP) to the Payload Data Segment to enable the scheduling of the data-acquisition facilities. Finally, the MPS reports on the success of the operations with respect to the plan.
- The On-Board Software Maintenance (OBSM) subsystem provides the engineers with an environment in which the on-board processor flight software can be maintained. The key issue for this subsystem is configuration control and availability. The software updates are obtained from the Software Maintenance Facilities (SMF).
- The Spacecraft Data and Evaluation facilities (Speval, WebSpeval) will archive spacecraft and ground-station data gathered throughout the duration of the Envisat mission and will allow this data to be retrieved and analysed later. A security-controlled, web-based interface is provided to allow remote access.
- The Communications Management Function (CMF) controls the transfer of data files between different functions inside and outside the FOS. The CMF has a database-driven routing algorithm, which also guarantees delivery in the case of anomalies. External users are separated from the FOCC by a firewall.

The staggered Flight Control System deliveries were validated and accepted using the Envisat Simulator. Testing using satellite hardware was only conducted with fully released software versions.

The Flight Dynamics System

The Fight Dynamics System for Envisat is an ESA internal development, operated by flight-dynamics experts. The services provided include:
- orbit determination and control
- generation of AOCS-related telecommand parameters for the central flight software
- monitoring and performance evaluation of the AOCS hardware and software, and testing and validation of all of the flight-dynamics products.

The Flight Dynamics System runs on a server/client platform (Sun/Solaris), which is highly redundant in terms of its key hardware. Each of the four disciplines mentioned above constitutes a self-standing and mutually-interfaced subsystem.

For the early part of LEOP (Fig. 4), the Orbit Determination and Control Subsystem is a very critical component, as its task is to determine the actual orbit. Ariane-5 will inject Envisat directly into its operational orbit. Immediately after the spacecraft's separation from the launcher, a rapid procedure will be started that allows all nine supporting LEOP ground stations to quickly locate and acquire the satellite. On the basis of this, a series of orbit-correction manoeuvres will be prepared to compensate for the relatively minor Ariane orbit-injection errors, and to initiate a drift phase of 1-5 weeks that will allow the precise phasing of the orbital positions of Envisat and ERS-2. Already two days after lift-off, orbit determination, prediction and control activities will assume a routine mode of operation.

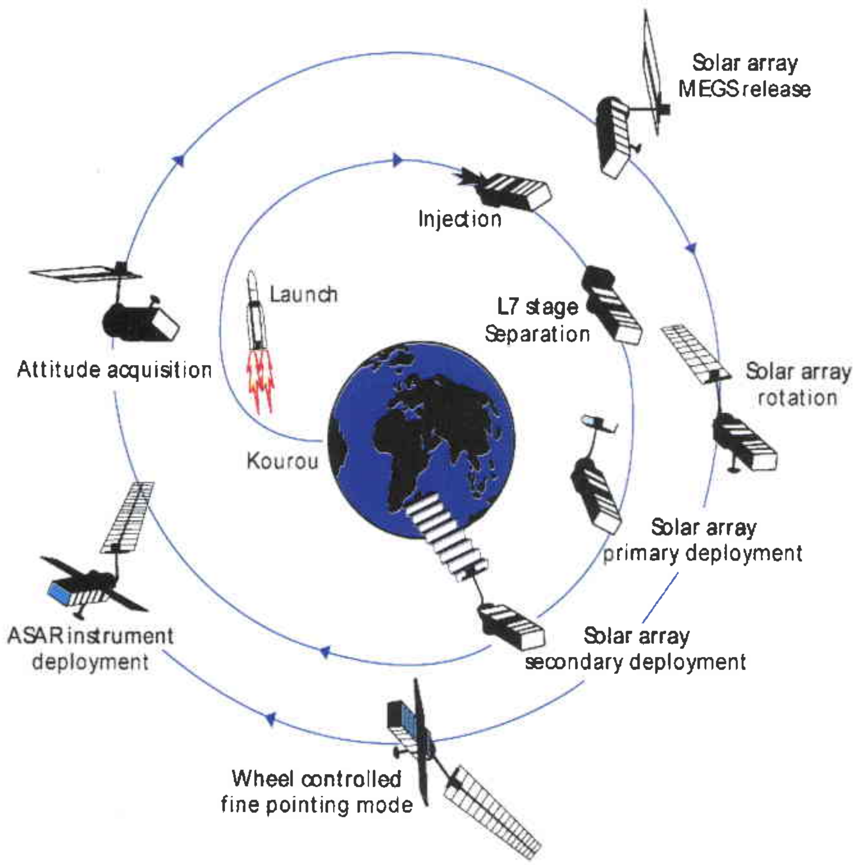

Figure 4. The Launch and Early Operations Phase (LEOP)

During the Routine Phase, the Orbit Determination and Control Subsystem will determine Envisat's orbit twice per day, predict its orbit for the next 8 days, provide this orbital information to the ground stations, and plan manoeuvres that will keep the orbit within the prescribed ground track, e.g. dead band.

During the LEOP, the AOCS Monitoring Subsystem will show how fast the satellite is rotating around its axes and will give an indication of how the automatic acquisition of the nominal attitude by the on-board control system is proceeding. It will also provide data shortly after spacecraft separation that will

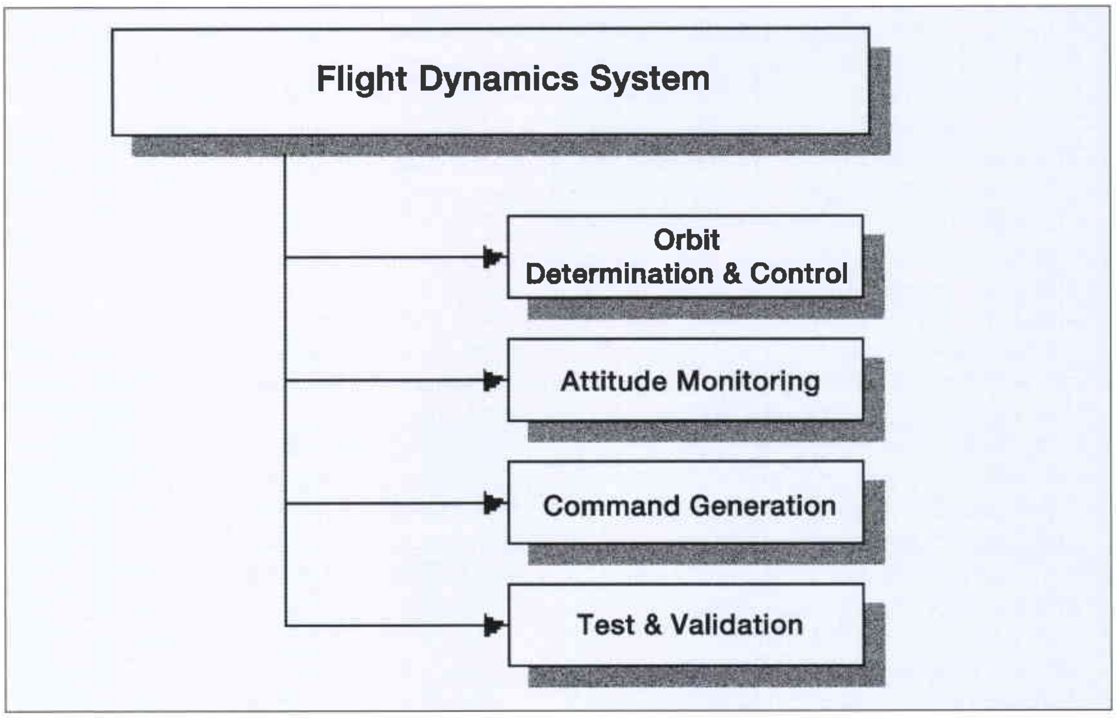

Figure 5. The Flight Dynamics facilities

indicate whether the solar array has been successfully deployed, which is essential for mission success. Further into the mission, the monitoring of spacecraft rates and other AOCS parameters such as reaction-wheel speeds and Earth-sensor measurements, will allow an assessment to be made of how well the on-board control algorithms and sensors are working, and how stable the satellite pointing is. This can then be compared to the estimates of spacecraft rates and attitude calculated by the on-board computer.

All the Flight Dynamics subsystems (Fig. 5) have been developed based on the similar ERS systems. For orbit determination, including high-precision orbit determination at the sub-decimetre level, this ERS experience has been used to develop the Navigation Package for Earth Orbiting Satellites (NAPEOS). This internal infrastructure product based on the flight-proven ERS orbit determination and control software can be reused for future Earth-orbiting missions.

An independent test and validation group has validated the mission-critical software developed as part of the flight-dynamics subsystem. The validation campaign included interface, single, subsystem and system tests and training. The key tools used in this campaign were a High-Precision Test Data Generator and a Tracking Data Generator, which generate realistic test data based on pre-defined attitude, orbit and ground-station parameters.

Once Envisat operations begin, the task of the test and validation group is to ensure the high quality of all products delivered to internal/ external parties.

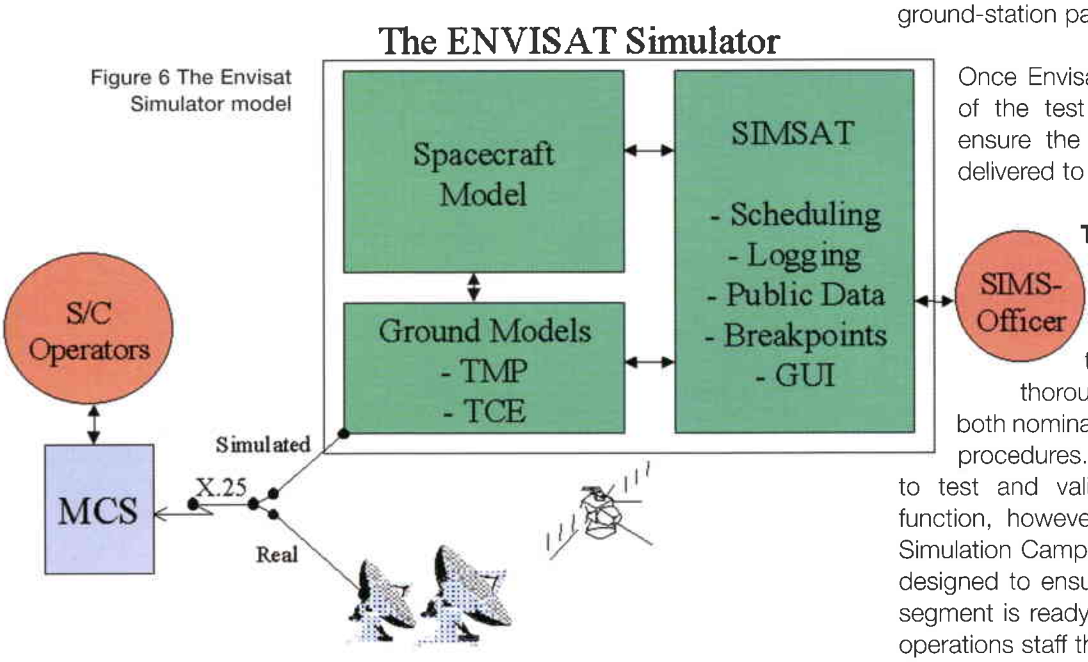

Figure 6 The Envisat Simulator model

The Simulator

The Envisat Simulator (Fig. 6) provides the spacecraft operations personnel with a training tool that allows the thorough testing and evaluation of both nominal and contingency operational procedures. In addition, it has been used to test and validate the FOS. Its primary function, however, is to support the Envisat Simulation Campaign prior to launch, which is designed to ensure that the complete ground segment is ready for the launch, including the operations staff themselves.

The Simulator runs on a DEC-Alpha work station and uses a generic 1750 emulator to model the satellite's on-board Central Communications Unit (CCU) and Payload Module Computer (PMC). This means that the actual flight software for both the CCU and the PMC can be executed in the Simulator, vastly adding to the realism and validity of the simulation.

The Simulator can be divided into three main parts: the infrastructure (SIMSAT), the spacecraft model itself, and the ground-equipment models. SIMSAT and the ground-equipment models are generic products that are used for a variety of the ESA spacecraft simulators. The spacecraft model is naturally unique and has been developed by industry using object-oriented analysis and design methods. It is therefore broken down in the same way as the spacecraft itself in terms of a Service Module, a Payload Equipment Bay, and the Payload Instruments. These components are then further broken down into the different components within these subsystems in a modular fashion.

Each delivery for the Envisat Simulator has gone through a series of tests before being accepted by the spacecraft operations team. Firstly, each module has been integration-tested by the developers, and then the whole system has been tested. The simulators were then formally delivered for 'provisional acceptance testing'. Once the Simulator had successfully passed such testing, it was released to the operations team for 'final acceptance testing'. These tests were based on the user requirements defined at the beginning of the Simulator's development lifecycle.

Operations

The operational concept is based on manual operations during critical phases and anomalies, conducted according to pre-defined flight operational procedures. All such procedures have been developed and validated at the FOCC (Fig. 7). During routine operations, schedules based on user inputs are generated automatically for operating the entire satellite.

Figure 7. The FOS Main Control Room

The mission operations can be divided into four distinct phases:
- the LEOP
- the Commissioning Phase, which can be further subdivided into a payload first switch-on (SODAP) and a Calibration and Validation (Cal/Val) Phase
- the Routine Phase, and
- the end-of-mission phase.

LEOP
During the initial LEOP, the prime objectives are to deploy the satellite appendages, to acquire the correct attitude, and to generate power from the solar array to re-charge the batteries. The FOS has to monitor the majority of the on-board auto-sequencing during the deployments. In the event of on-board contingencies, the flight control team has to react quickly to determine the cause of the anomaly and to execute the pre-defined recovery operations that have been practised many times during the simulations.

The satellite design allows only about four orbits without power from the solar array, which makes any contingency recovery extremely time-critical. This is why a dense network of nine ground stations with a fully redundant infrastructure has been built.

Two mission control teams operating in two shifts, 24 hours per day, will be available in the Control Centre. During the second part of the LEOP, acquisition of the operational orbit will be initiated and the Advanced Synthetic Aperture Radar (ASAR) antenna will be deployed. This phase will last approximately 1 week.

Commissioning
Once the LEOP has been completed, the initial commissioning of the Service Module, Payload Equipment Bay (PEB) and Instruments will commence. In this phase, the PEB and the instruments will be switched on incrementally and the in-flight performances of the various on-board subsystems and of the ground segment will be verified. Also as part of this phase, the Ka-band antenna will be deployed and some instrument covers will be released.

The instruments will then be calibrated and their Earth-observation products validated during dedicated campaigns. The overall duration of the Commissioning Phase will be approximately 6 months. With the exception of a few critical switch-on and deployment operations requiring extended coverage, a single Kiruna and/or Svalbard pass per orbit is sufficient to command and control the satellite during this phase.

The operational concept evolves around operations by procedure for the initial switch-on and deployment-and-release activities and automatic scheduling by the FOS Mission Planning System. Step-by-step, the latter will take over the planning and commanding of the Payload Module's Data Management System and then the instruments.

Routine Phase
The prime objective in the Routine Phase is to generate high-reliability Earth-observation products, as requested by the users. Most routine activities during this phase will be generated by dedicated software tools and procedural interaction will nominally be limited to routine monitoring, the up-linking of tele-command schedules, and maintenance activities (e.g. orbit maintenance). Routine AOCS commands will be generated automatically during this phase by the Flight Dynamics System, based on the latest orbit-prediction data.

For the Payload Equipment Bay and Instrument operations, the Mission Planning System will schedule the activities up to one year in advance, based on external requests for specific operations from the Payload Data Segment and Announcement of Opportunity centres, and a global observation plan. The resulting command schedule for the next 24 hours or more will then be up-linked to the time-tagged queue of the Payload Module Computer well in advance of the actual operation. The schedule is executed automatically on-board as long as the satellite performs nominally. The ground control system maintains an accurate model of this queue and verifies the correct execution automatically during the next ground-station pass when the on-board history telemetry formats are received.

The short duration of the individual ground-station passes (maximum of around 12 min of coverage) also calls for optimum uplinking at maximum rate. In the event of an on-board anomaly, the spacecraft will normally switch into a safe configuration. In this case, the FOS has to analyse the problem and recover the platform or instrument to a nominal mode of operation as safely and as quickly as possible.

Envisat has approximately 50 different on-board processors. The FOS is fully responsible for the maintenance of the instrument and Payload Module Computer software, and shares responsibility for Service Module software maintenance with industry during the Routine Phase. Dedicated software-maintenance facilities for the various processors and an On-

Board Software Maintenance System (OBSM) are available to generate and validate new on-board software images, to generate patch commands, to verify correct execution, and to perform configuration control for the various on-board software packages.

FOS validation

The FOS system definition has been driven by requirements defined by the operational team. The development effort has been conducted in close co-operation with the project team and industry. The FOS includes approximately 2700 user requirements.

Each subsystem has been developed in a staggered way and each staged delivery has been separately tested and accepted by ESA. These deliveries have each also been the target of one of the four System Verification Tests (SVTs). The SVTs are the tests in which the ground segment meets the satellite, and the four SVTs have therefore been the driving milestones for the entire project. For each SVT, a system has been integrated consisting of increasingly complex delta-deliveries. The process of building and integrating this hierarchy of deliveries was defined at requirement level by each requirement having an attribute identifying the particular SVT for which it was needed.

The Spacecraft Operations Manager and his team have conducted the SVTs using prototype Flight Operational Procedures. Although the main objective of the simulation programme is to train the operational teams, it also provides a final validation of the system and the associated Flight Operational Procedures.

The FOS System Operation Validation (SOV) tests validated the entire LEOP configuration to support both nominal and non-nominal LEOP scenarios and routine operations. An extensive simulation campaign will be performed before the launch, to validate all the nominal and contingency operational procedures, and to ensure coherence and smooth interaction between the FOS and the LEOP stations .

Once validated, the FOS configuration will be frozen and kept under strict (ISO-qualified) configuration control.

Conclusion

The development of the FOS started with an in-depth definition of requirements involving both the engineering and operations teams. The Envisat mission has also made systematic use of existing facilities previously developed and validated for the ERS mission, wherever possible. This approach, combined with strict enforcement of the requirements throughout all FOS development phases and for all FOS elements, has allowed the timely delivery of a Flight Operations Segment that is truly ready to be used. The close involvement of the FOS operations staff during the early phase of the development has helped to ensure a smooth and natural transition between the development and operations phases. esa

The Payload Data Segment

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The Envisat Payload Data Segment (PDS) provides the services needed for the exploitation of all of the instrument data. Its development has been the subject of a contract between ESA and Alcatel Space Industries as the Prime Contractor, supported by a consortium of thirteen companies. Twenty-three different facilities or subsystems have been developed and the result is a large distributed system with operational sites in seven European countries.

Introduction

The Envisat Ground Segment is composed of the Flight Operations Segment (FOS) and the Payload Data Segment (PDS). The main functions of the PDS are:

- aquisition of the low- and high-bit-rate instrument data via the X-band channel when in direct visibility of the Envisat satellite, or via the Artemis data-relay satellite's Ka-band channel
- processing (systematic or on-request) of the received data in near-real-time (within 3 hours after sensing) or off-line, up to Levels-0, 1 and 2
- short- or long-term archiving of the products generated
- dissemination of the products to scientific and commercial users
- provision of user services.

The mission users may consult the archives, request past or future Envisat products, and plan instrument observations for the ASAR and the MERIS full-resolution instruments.

The PDS operations are co-ordinated from the Payload Data Control Centre (PDCC) located at ESRIN, in Frascati (I). The Envisat products that it provides are always in the form of computer-readable files, classified according to a progressive level of processing:

- *Level-0*: reformatted, time-ordered satellite data (no overlap) in computer-compatible format
- *Level-1b*: geo-located engineering-calibrated product, either 'unconsolidated' (i.e. generated in near-real-time) or 'consolidated' (i.e. generated off-line)
- *Level-2*: geo-located geophysical product generated in near-real-time or off-line
- *Browse*: subset of Level-1b, for quick viewing and product-selection purposes.

In total, the the PDS delivers 77 different types of products. Processing algorithms have been developed by a number of Expert Support Laboratories (ESLs) and are implemented in the PDS as specific Instrument Processing Facilities.

PDS architecture

The PDS comprises the following Centres and Stations:

- The *Payload Data Control Centre (PDCC)* at ESRIN in Frascati (I) is responsible for the instrument and ground-segment planning and for the overall PDS monitoring and control. It also co-ordinates the user services and provides quality and engineering support for the products.
- The *Payload Data-Handling Stations (PDHS)* in Frascati (Ka-band) and in Kiruna, Sweden (X-band) acquire measurement data down-loaded from the spacecraft, process it and disseminate the products, according to PDCC directives. A short-term rolling archive is provided. Local services are also offered to users. A reduced PDHS will be installed at Svalbard, to provide back-up support for Level-0 data acquisition and processing, complementing the five daily Kiruna-blind orbits.
- The *Payload Data-Acquisition Station (PDAS)* in Fucino (I) acquires only measurement data

(in X-band) and forwards it to the PDHS station at ESRIN for processing.
- *The Low-rate Reference Archive Centre (LRAC)* in Kiruna archives and processes the global low-rate data off-line, to provide a complete consolidated low-rate Level-1b data set for the ESA Developed Instruments (EDIs) and ASAR-LR Instruments, and a pre-consolidated Level-1b product for other Announcement of Opportunity Instruments (AOIs). Local services are also offered to internal users.
- The *Processing and Archiving Centres (PACs)*, located in various ESA Member States, archive and process off-line high-rate data and generate off-line Level-2 products for regional high-rate or full-resolution instruments and global low-rate instruments. There are six PACs: UK-PAC, D-PAC, I-PAC, F-PAC, S-PAC and E-PAC. The Finnish Meteorological Institute (FMI) is associated with the D-PAC.
- The *National Stations (NS-Es)*, located in ESA Member States, acquire data and provide ESA services.

Figure 1 shows the locations of the various PDS Centres and Stations and lists the main functions of each of them (except the PACs, where only the instruments are listed).

PDS services

The PDS design is based on the development of a limited number of basic facilities implementing a single function, and the systematic re-use of those facilities as building blocks in the various centres at the various geographical locations. For example:
- all centres and stations offer user services based on the same User Service Facility (USF)
- low-bit-rate processing at the two PDHSs and the LRAC is performed using the same hardware platform and software
- ASAR processing at the two PDHSs and three PACs (UK-PC, D-PAC and I-PAC) is also performed using the same hardware platform and software.

The various PDS services, implemented using one or more facilities in combination, are

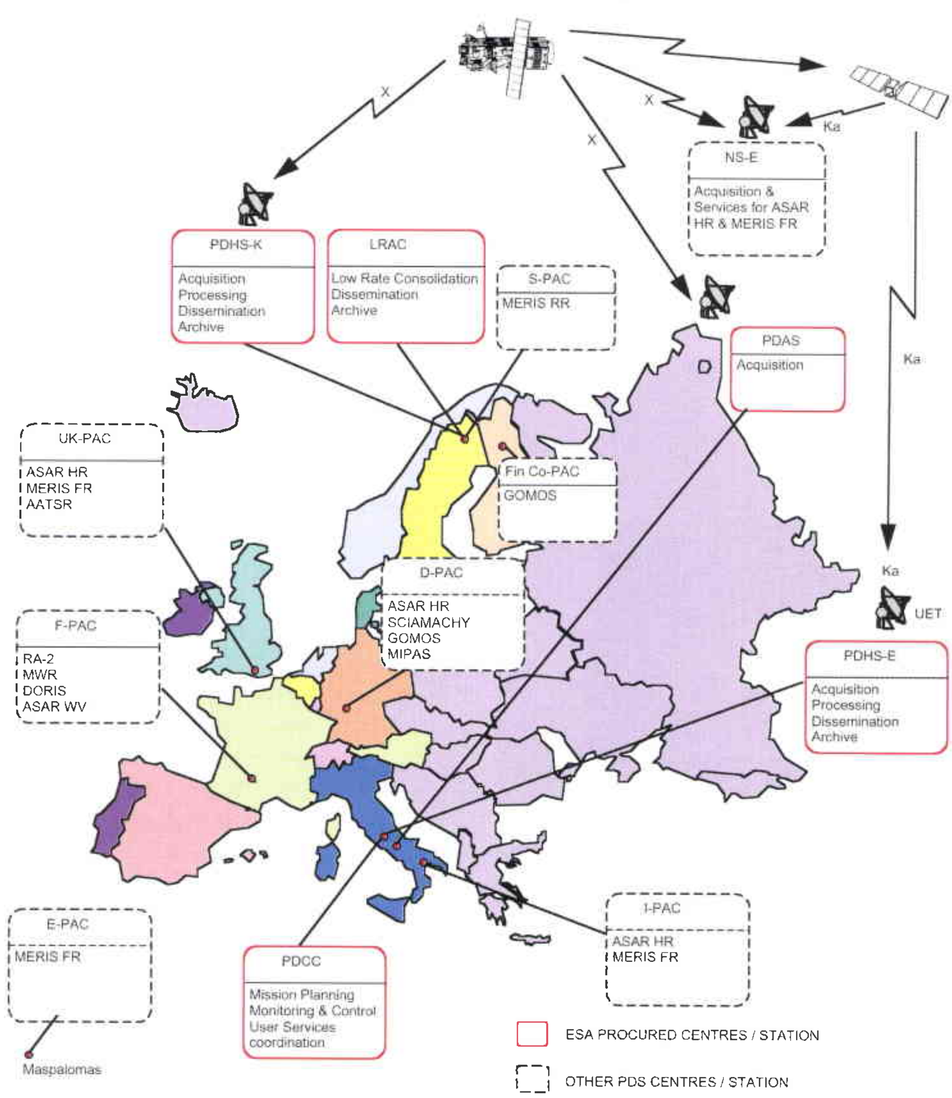

Figure 1. Locations and primary functions of the various Payload Data Segment (PDS) centres and stations

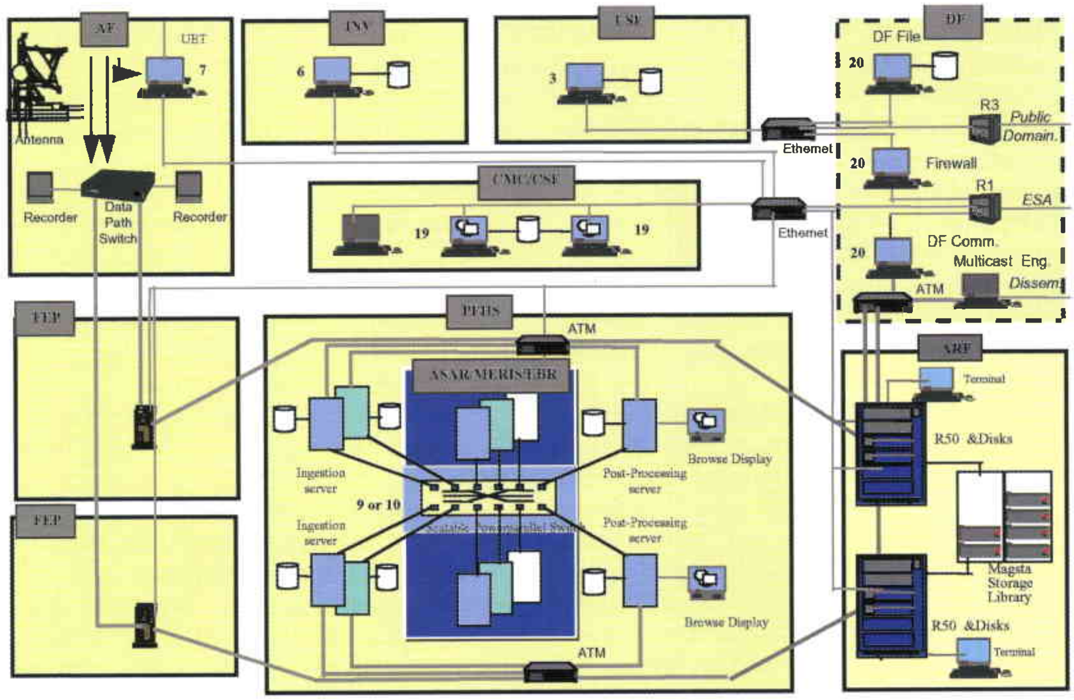

Figure 2. The PDHS architecture and facilities

acquisition, data processing, archiving, dissemination, user services, mission planning, monitoring and control, and ancillary services.

Acquisition
Envisat downlinks its instrument data via two simultaneous time-multiplexed 100 Mbps links, which carry both the real-time and on-board-recorded observational data. On-board solid-state recorders allow for low-rate and high-rate instrument recording, with up to 12.5 minutes of ASAR high-rate data or up to 40 minutes of MERIS full-resolution data.

Figure 3. The User Earth Terminal reception antenna at ESRIN, for Envisat data acquisition via Artemis

The Kiruna-Salmijarvi station includes a 15 m X/S-band receive/ transmit antenna, which has already been used for ERS-1 and ERS-2, and serves X-band payload acquisition and TT&C operations. The station is also equipped with a new 13 m X/S-band receive/transmit antenna, allowing increased flexibility and serving as a backup. The Frascati station includes a 12 m Ka-Band receive-only antenna, a so-called 'User Earth Terminal' (UET), to acquire Envisat data relayed via Artemis. Both stations are equipped with new multi-mission programmable demodulators, developed under the ESA ARTES-4 technology programme and specifically tailored for Envisat.

The nominal acquisition scenario with the Artemis Ka-band inter-orbital link available is based on the Kiruna (X-band) and Frascati (Ka-band UET) stations. If the Ka-band is temporarily unavailable, the back-up scenario is to use the Kiruna and Svalbard stations. At each station the data is received, demodulated, real-time de-multiplexed and ingested into the processing facilities for Level-0 product generation and archiving. As a backup measure, raw data is always recorded on high-rate digital recorders and can be replayed if necessary for backlog ingestion. In the nominal scenario, both stations will operate on an equal-share basis, covering complementary acquisition periods of twelve hours per day and seven passes each.

Data processing
The Front-End Processor delivers instrument source packets to the Processing Facility Host Structure (PFHS). The delivery is done in near-real time at half the acquisition rate, making it

possible to ingest a complete pass well before the start of the next acquisition. The PFHS hosts the different Instrument Processor Facilities (IPFs). In particular, it manages all of the production activities, performs the generation of Level-0 products from the data received via the FEP, and distributes the higher-level production work between the different IPFs. Seven IPFs have been developed, one for each instrument: ASAR, MERIS, AATSR, GOMOS, RA-2/MWR, MIPAS, SCIAMACHY. These IPFs generate the Level-1b, Browse and Level-2 products. The PFHS may also retrieve Level-0 data from the archive for the high-level processing of previously acquired data.

The PFHS architecture is based on a simple robust and scalable concept: a number of autonomous computers (nodes) connected by a high-speed parallel switch (IBM-SP2 architecture). Four nodes are dedicated to data ingestion and Level-0 processing, and two are dedicated to data output and overall PFHS management. The remaining nodes each contain the software of all seven IPFs and can be dynamically activated to behave as any required instrument processor. This makes it possible to increase the processing capacity just by adding new nodes, and to optimise the resource usage so that it can be adapted easily to any mission-utilisation scenario, whilst still ensuring a minimal impact from any hardware failures.

The LRAC in Kiruna will ingest the data from low-rate instruments received at the PDHSs and consolidate them by regenerating orbit-based products.

Archiving
The PFHS output products are sent to the Archiving and Retrieval Facility (ARF), where they are permanently stored on tape (standard IBM-3590 10 GB magnetic tapes). Each ARF is equipped with a media-handling robot allowing unattended archiving and retrieval operations.

At the PDHSs, data is archived temporarily for a period of about four weeks, covering the time needed to transfer tape copies to the final archiving destinations at the PACs.

Dissemination
The PDS products (Level-0, 1 and 2) are made available to users either:

- in Near Real Time (NRI), 3 hours or 1 day after sensing
- off-line, several days or more after sensing.

Electronic data delivery is also available:
- via the Internet, through the web-based user services on-line archive for the smaller products (typically below 1 Mbyte), such as browses and a configurable set of high-level products
- via the Data Dissemination System based on Direct Video Broadcasting (DVB) technology, operated at 2.5 Mbps in broadcast- or multicast-mode for fast delivery (within three hours or one day of sensing), to users equipped with the corresponding receiving facilities.

Figure 4. The processing facilities at ESRIN

The physical-media service allows users to receive products on one of several media – CD-ROM, Exabyte, DAT, DLT, and 3590 – selectable at the time of ordering.

User Services
The Envisat PDS User Services provide a uniform access point for all Envisat users to access a wide range of services, mainly for the consultation of Envisat PDS archives, mission and product information, and the ordering of past or future products. In the latter case, the user can either select from already planned acquisitions, or request the specific planning of satellite observations for regional-mission instruments (ASAR and MERIS).

The User Services are implemented via three different facilities: the User Services Facility (USF), providing the web-based Internet access, the Inventory Facility (INV), a database containing the mission data catalogue, and the User Services Coordination Facility (USCF), coordinating the distributed USFs and managing ancillary services like user registration and order follow-up.

The architecture is distributed, with instances of the USFs and INVs at all PDHS and PACs providing points of access in several countries. A user accessing any of the USFs will be provided with the same services and the same data visibility. Each INV holds a catalogue of the data archived in its centre or station. A central INV in the PDCC automatically receives daily snapshots of the distributed catalogues, thereby providing a universal central PDS catalogue. More detailed information about the User Service Facility may be found in a separate article this Bulletin.

Mission planning
A High-Level Operations Plan (HLOP) defines the Envisat mission-operations strategy and high-level operating rules. The HLOP is translated into a Reference Operations Plan (ROP), which defines mission scenarios for the whole mission, to optimise the utilisation of the instruments and ground resources with respect to the users' requests for products, the scientific objectives of the various instruments, the satellite and ground-segment constraints, and the instrument calibration and characterisation requirements.

The ROP is used both in the Payload Data Segment (PDS) and the Flight Operations Segment (FOS), and consists mainly of a set of files used for configuring and driving the PDS–FOS mission planning and ground segment. The ROP, for example, defines global instrument utilisation according to a Global Mission Definition (GMD) and provides the Background Regional Mission (BRM) utilisation for regional instruments, defining the default observations to be carried out in the absence of overruling user orders.

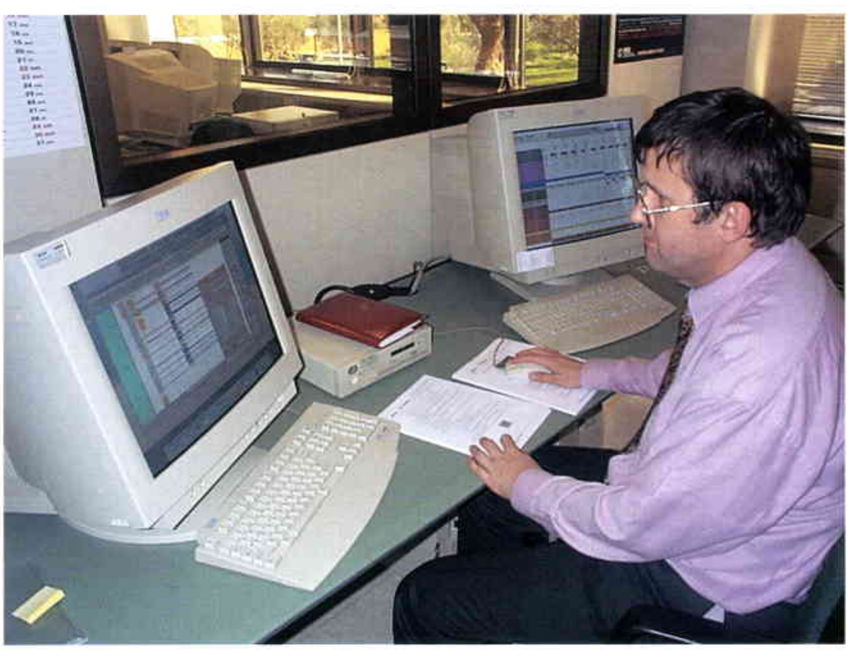

Figure 5. Operating the mission planning facilities at the PDCC

The Envisat Mission Planning includes three components:

- The *Global Mission (GM)* defined by the ROP in the form of orbit scenarios per instrument MERIS RR, GOMOS, MIPAS, RA-2, MWR, AATSR, SCIAMACHY, DORIS. The FOS, using the GMD file generated by the RGT, performs the Global Mission planning.
- The *Background Regional Mission (BRM)*, addressing ASAR HR, ASAR LR and MERIS FR, defined on the ROP as a set of orbital segments or geographical zones enabling detailed planning of instrument operations.
- The *Regional Mission (RM)*, addressing ASAR HR, ASAR GM and MERIS FR, driven by user requests, expressed in terms of zones and/or segments.

At the PDCC, the Mission Control Facility channels the users' observation requests, received via USFs and analysed and filtered for constraint compliance, to the FOS in the form of a weekly Preferred Exploitation Plan. This plan defines the required regional instrument activities for a period of typically two weeks ahead. The FOS analyses the request, checks compliance with satellite utilisation constraints, and reports back to the PDS with a Detailed Mission Operation Plan (DMOP), defining the exact satellite planning for all instruments, both global and regional.

By processing the DMOP, the Mission Control Facility creates a Global Acquisition Plan (GAP), defining the high-level activities to be carried out in each of the PDS operational centres and coordinating their complementary operations. For example, acquisitions at Frascati and Kiruna should be followed by reception of products at the LRAC for low-rate-instrument consolidation and the reception at the PACs of circulation tapes for archiving and high-level processing.

Monitoring and control
The Global Acquisition Plan (GAP) is processed by the Ground Segment Planning (GSP) facility within the PDCC, which elaborates the detailed directives to be executed for each of the operational centres, taking into account the available centre or station resources and operational statuses. As a result, the GSP generates 48-hour plans which are sent to the stations, and medium-range plans (two weeks) which are sent to the LRAC and PACs.

At each centre or station, a Centre Monitoring and Control (CMC) facility receives the plans and performs the detailed Centre scheduling. The CMC uses these directives to generate final facility instructions, which effectively command the facilities' operations. In return, the facilities provide instruction reports detailing all information associated with the instruction's execution, such as actual product ingestion, generation and archiving times, results, diagnostics and error codes. The CMC consolidates this information into Centre production and performance reports, which are then forwarded to the GSP. The GSP compiles all Centre reports and builds a database with details of the operations, which is then used to build management reports and to investigate any problems.

The CMC also provides for real-time Centre monitoring via an interactive graphical user interface, allowing the operators to supervise progress in the operations and take corrective actions when needed. In addition, the CMC also manages local user orders, received via the USF, which can be serviced locally without involving the PDCC, e.g. deferred production from locally archived data sets.

As indicated above, the monitoring and control architecture provides several encapsulation layers (DMOP, GAP, 48 h and MR plans, centre schedules and facility instructions), containing detailed knowledge in higher layers and permitting centres and stations to be reconfigured with no impact at PDCC level. In particular, the GSP and CMC are configured with special Operation Constraints Definition (OCD) files, written in a language specifically developed for the PDS. These files provide the GAP-to-plans and plans-to-instructions mapping in a highly flexible way, and allow the modification of or the creation of new operational sequences as a result of progressive operations experience without the need to modify existing software. This has proved to be a very powerful tool during PDS integration.

Ancillary services
Other services internal to the PDS have also been implemented:

- The Product Quality Facility, recently renamed QARC (for Quality Assessment and Reporting Computer), provides an integrated platform with functions for the long-term characterisation of the PDS and Envisat satellite systems and instrument performance, as well as the capability to perform detailed interactive analyses of PDS products. With these functions, the PQF provides the elements needed to support the investigation of anomalies, queries and complaints from users.
- Auxiliary data circulation is very important for the success of the production services. Such data includes instrument calibration and data, and orbit-element data. The auxiliary data circulation is centralised and coordinated by the MCF.
- Common Services Facilities (CSF), regrouping all of the components that are common to several facilities, providing UNIX middleware services, such as common file- and message-transfer mechanisms, back-up, installation, host redundancy, etc. Together with the CSF, a Detailed Data Dictionary (DDT) containing interface-control databases and centralised definition of formats has allowed many of the integration problems that often occur in such a large development effort with several different suppliers, to be avoided.
- The Engineering Support Facility (ESF) provides integrated configuration-control services and a reference platform that can be configured as any PDS centre or station and will be used for maintenance, anomaly-investigation, testing and validation purposes.

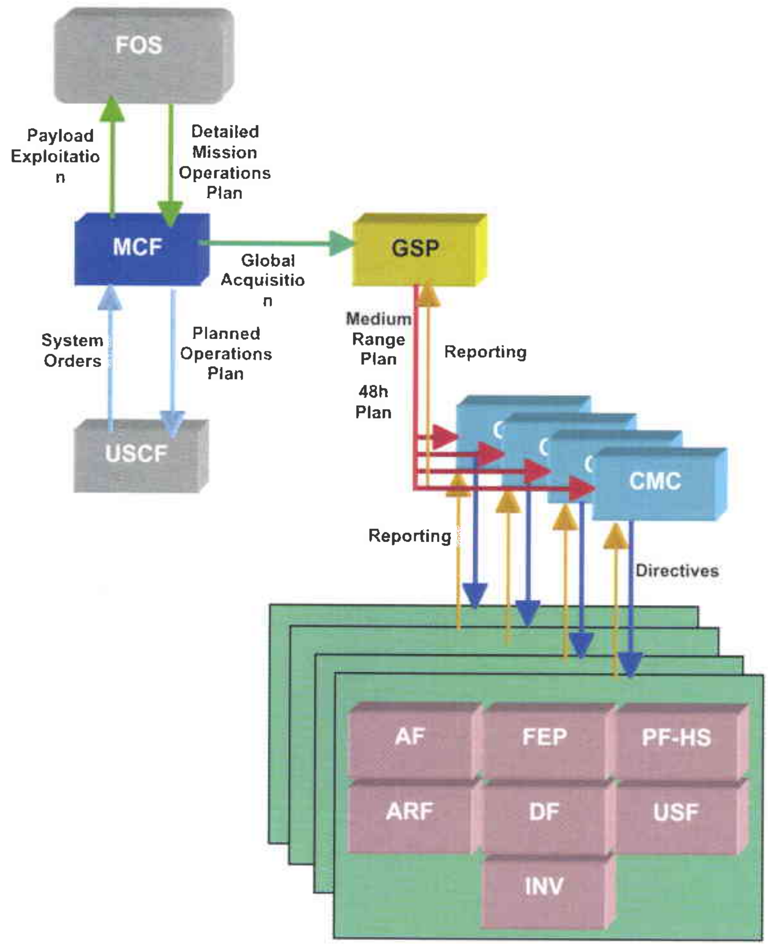

Figure 6. The mission-planning loop in the PDS

PDS development and validation

The PDS's development and validation has followed a classical approach, starting with testing and acceptance activities at unit and component level and progressing to facility, station or centre level. The validations of the PDS instrument processors used Level-0,

Figure 7. Acquisition facility equipment

Level-1 and Level-2 instrument products and auxiliary data, simulated by the Expert Support Laboratories (ESLs). The end-to-end validation of the PDS facilities used a highly representative satellite-to-ground data stream, simulated by the Data Flow and Format Simulator (DFFS).

The PDS validation started with the validation of the PDHS in Frascati, followed by that of the PDCC, also in ESRIN, then that of the PDHS in Kiruna, then that of the LRAC also in Kiruna, and ended with the acceptance of the complete PDS.

Additional PDS validation testing using real satellite instrument data recorded during the satellite assembly, integration and test (AIT) phase has been performed to verify the compliance of both the satellite and the ground segment with the satellite-to-ground interface specifications. The Envisat mission-planning loop, involving both the FOS and PDS, has also been extensively tested on a separate representative platform as part of the GSOV.

Conclusion

The development of the Payload Data Segment has shown that it is important to have a set of detailed requirements, interface-control documents, mission conventions and technical guidelines precisely defined at an early stage in the project. They also need to be rigorously applied to all of the components of such a widely distributed system. The decomposition of the overall PDS into manageable building blocks avoided the duplication of software or hardware developments, and allowed a coherent and optimised set of integration and validation activities at all of the various PDS locations.

One of the major challenges during the Payload Data Segment's development was the generation of a representative and coherent set of test data, allowing the static and dynamic integration and validation of the test activities at the facility, centre and the overall-PDS levels.

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Envisat User Services

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The User Services will play a major role within the Envisat Payload Data Segment (PDS). Based on Internet technologies and a distributed architecture, they provide efficient access to Envisat products and information and offer a wide variety of on-line services to the user community.

Introduction

Envisat will be the first ESA Earth-observation mission to offer dedicated user-community services via the Internet. Individual users, distributing entities and value-adding companies will have easier and faster access to Envisat products, data and information (catalogue meta-data, browse images, processing algorithms, product descriptions, etc). The reduction in manual intervention will also improve the efficiency of both the Envisat Order Desk and Envisat Mission Planning operators.

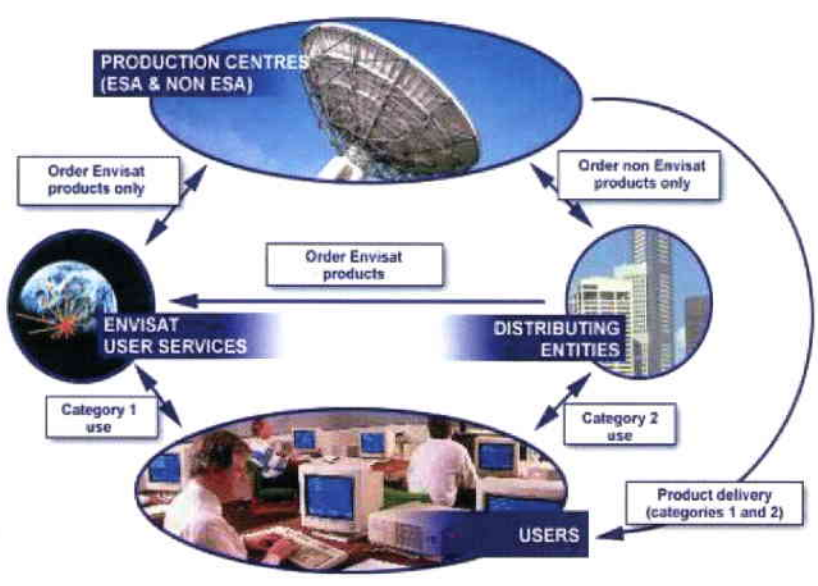

Figure 1. Envisat product distribution policy

The Envisat User Services have been developed and tested via an industrial contract by Datamat, under the responsibility of the Envisat PDS Prime Contractor Alcatel Space. The system integration and validation has been tested both at Datamat's premises and at ESRIN. Additionally, ESA has conducted its own testing with the help of the Belgian company RHEA.

The User Services

User and distribution policy

There are two categories of use defined in the Envisat Data Policy, as laid down in February 1998:

Category 1
- Research and applications development supporting the mission objectives
- Research on long-term issues of Earth-system sciences
- Research in preparation for future use
- ESA internal use for calibration, validation, and quality assurance.

Category 2
- All uses not falling under Category 1, including operational and commercial use

The Product Distribution Policy is illustrated in Figure 1, which shows the data flow for orders and the product-distribution flow depending on the category of use.

The implementation of the Envisat User Services has been driven both by the Envisat Data Policy and the high-level requirements of the High-Level Operations Plan (HLOP).

Available services

Table 1 provides a list of services offered to users, some of which are freely accessible,

Table 1. List of User Services

Category	Service	Description	Availability
Information Gathering	• Directory & Guide • News & Bulletin Board	• Products & services information • What's new, messages from users	• free • free
Product Search and Preview	• Inventory • Browse • Software tools	• Catalogue of archived products • On-line preview for AATSR, ASAR, MERIS • Local inventory & browse	• free • free • free
Product Order	• Archived products • On-demand products • Future products • Auxiliary data • Subscription • Special acquisition	• All products already in archive • Child products, scenes • Products to be acquired and processed • For reprocessing and quality control • Systematic reception over a given timeframe • For Stations only	• registered • registered • registered • registered • registered • registered
Other Orders	• Software tools • Directory & Guide updates • Inventory updates	• Product visualisation • For local consultation • For local consultation	• registered • free • free
User Administration	• User registration • Account information • Order information	• Request for a registered account • Personal data, user quota, ... • Order status, cost, ...	• free • registered • registered

while others are reserved for registered users. In particular, product ordering is restricted in order to respect the Envisat Data Policy.

Distributed User Services architecture
The Envisat User Services are characterised by a distributed architecture, offering the same services to the users through several access points in a fully transparent manner. There are three types of facilities:

Facility name	Function
USF (User Service Facility)	Web access point from the Internet
USCF (User Service Coordination Facility)	User and order management; coordination of the USFs
INV (Inventory)	Catalogue of products archived in the PDS

There is one of each facility in every Payload Data Section Centre and Ground Station, except the USCF which is installed only in the Payload Data Control Centre at ESRIN, Frascati, Italy. The USFs and INV are currently installed in several centres distributed across Europe (Fig. 2):
– Processing and Archiving Centres (PACs)
– Payload Data-Handling Stations (PDHSs)
– Payload Data Control Centre (PDCC).

The USCF makes the exchange of information relating to the user and order management between User Services Facilities possible. Because information is exchanged between the User Services Facilities and the Inventories, the user has a complete view of the payload data section regardless of which he/she is connected to. Users may access any USF and will have access to exactly the same services.

Those facilities have multiple interfaces with several other PDS facilities: the Monitoring and Control Facility, which is in charge of the mission planning, the various processing and archiving facilities (PFHS, ARF, and instruments processors), the Centre Monitoring and Control facilities, the Dissemination Facility and the Product Quality Facility. The order requests are automatically sent by the USF to the Monitoring and Control Facility via the USCF for the production of the Payload Exploitation Plan, which is transmitted to the FOS Mission Planning facility at ESOC. This data flow is illustrated in Figure 3.

User interfaces
In addition to the traditional communication media between the users and the Envisat Order Desk, users may access the User Services via the USF in two ways (Fig. 4):
– Interactively, with a Web browser
– Non-interactively, using a dedicated program on his/her computer to exchange information with the USF over the Internet ('computer-to-computer' access).

In terms of catalogue queries and order requests, both the interactive and non-interactive methods of access offer the user community exactly the same services.

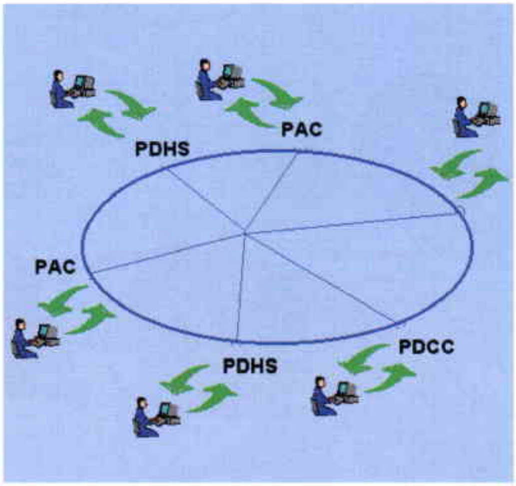

Figure 2. The distributed architecture

The interactive user interface
This man/machine interface has been developed using the latest web technologies, allowing on-line users to access the Envisat User Services via their Web browsers. It has also been harmonised with two other existing user interfaces, 'EOLI' and 'EOWEB', which are the front-ends to the ESA MUIS (on-line multi-mission catalogue) and DLR ISIS information systems, respectively. Currently, 17 ESA and non-ESA mission instruments are referenced by the MUIS catalogue, to which the Envisat mission instruments will be added. MUIS contains more than 7 million entries, 200 000 passes of browse images, and provides access to this information within a few seconds. MUIS is accessible via http://odisseo.esrin.esa.it/eoli/.

The core of the user interface is the EOLI Java applet. In operation for several years, this software module has been refined and improved significantly with the help of feedback from the user community. In the same spirit, the Principal Investigators participating in the rehearsal of the Envisat Calibration and Validation campaign also tested the Envisat user interface, and many of their comments and ideas have already been implemented.

The interface has been designed to allow the user to perform almost all operations through a single WWW window, using one of two interface levels provided:
- 'Advanced' for advanced users, which has features specific to Envisat instruments
- 'Standard' for most users, which is fast and easy to use.

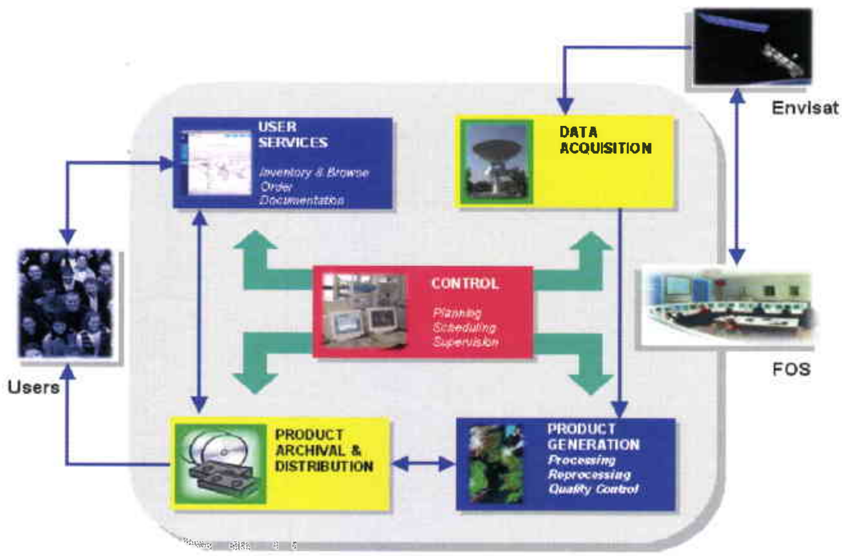

Figure 3. Interface overview

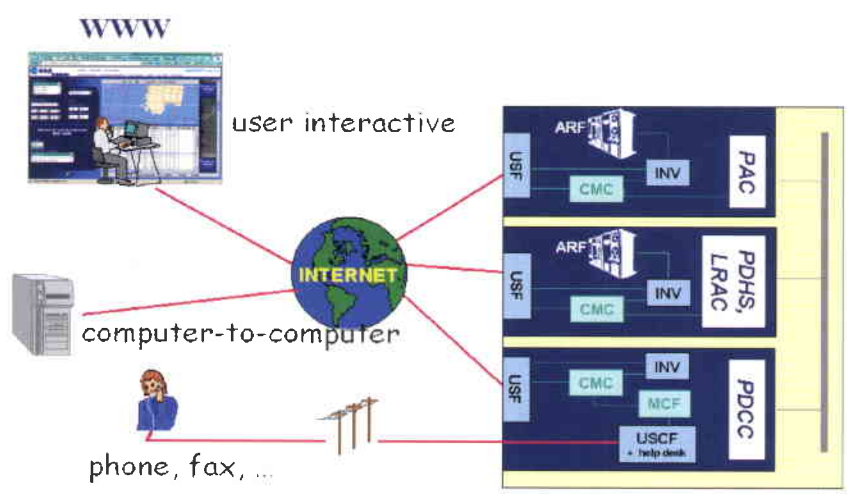

Figure 4. The user interfaces

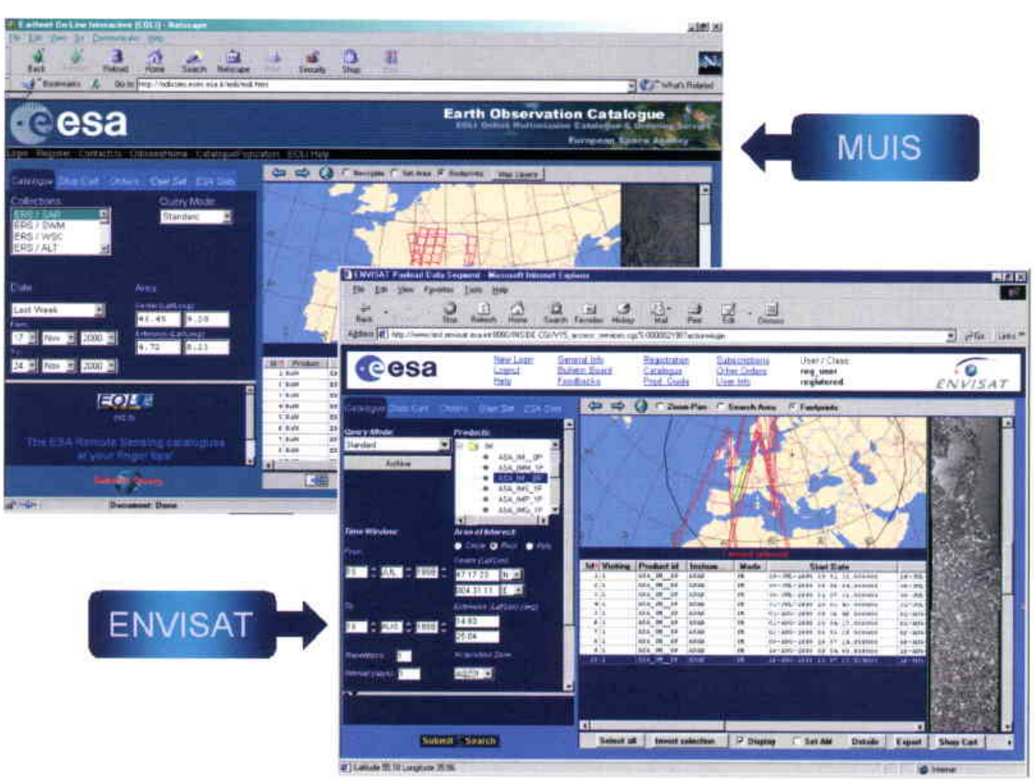

Figure 5. The harmonised user interfaces of Envisat and MUIS

The non-interactive computer-to-computer interface
The USF architecture allows computer programs running on the client's platform to automatically send catalogue queries, receive answers from the USF, and submit requests for orders. The dialogue between the client's computer and the USF is established via the Internet. The Belgian company RHEA has developed a library of routines, written in PERL, that can be run on the user's side. This library software package is available on request and can also be downloaded via the interactive user interface. Using this PERL library is quite simple, as the user specifies the query parameters inside an ASCII text file, using the 'parameter = value' formalism (PVL). Responses to queries are sent back to the calling client platform either as an HTML or an ASCII file.

User Services functions

Directory and Guide
This service provides information on the Envisat products (availability, format, location, algorithms, auxiliary data, best images) as well as information on the Centres (addresses, telephones, faxes, e-mails, activities descriptions, links to WWW home pages), as indicated in Figure 6.

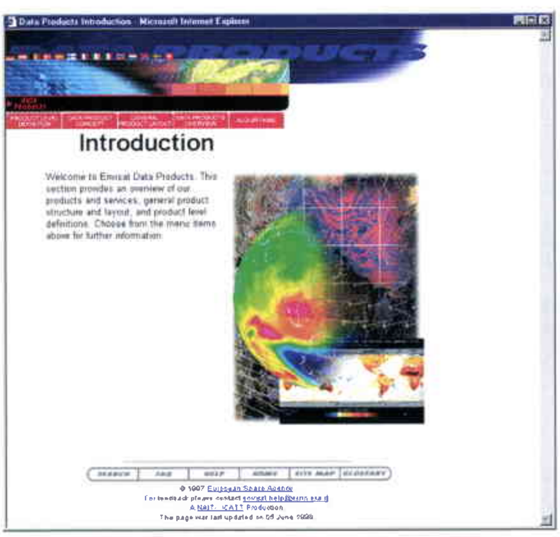

Figure 6. The Directory and Guide

News and Bulletin Board
The News and Bulletin Board gives the latest news on Envisat in terms of products, algorithms, services, centres, conferences, etc. (Fig. 7). It is a discussion forum in which users can exchange mission-related information.

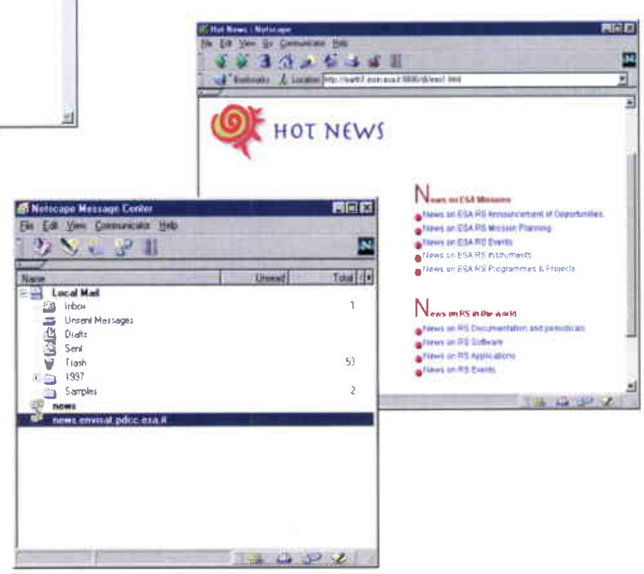

Figure 7. The News and Bulletin Board

Catalogue - Inventory
One of the numerous free services offered to users is access to Catalogue (INV) and Browse images. Within each PDS Centre and ground station, the INV facility contains meta-data describing the products stored in the Local Archive Facility. The Inventory at the Payload Data Control Centre in Frascati has a particular role in that it duplicates the contents of all the other Payload Data Segment INVs. A query issued from a single USF is passed to all of the inventories. The responses from all of the INVs are then grouped and presented to the user in a single HTML or ASCII file.

In fact, when issuing a query through the USF, the user can access not only the INV meta-data corresponding to the archived products, but also information on future acquisitions already planned, or ones that could be scheduled on user request. This allows the user to formulate in his/her query time-windows that overlap both the past and the future. Query parameters may be standard (product type, time, geographical area) or specific, and more detailed parameters are contained within the MPH and SPH products, such as swath and polarisation for ASAR. Figure 8 shows the Catalogue Query and Responses window.

Browse products (AATSR, ASAR and MERIS) are systematically converted into browse JPEG images when received by the ARF. These browse images are then forwarded to all the PDS User Service Facilities. Each facility carries up to six months of browse images on-line.

Browsing
Browse images for the three Envisat imagers (AATSR, ASAR and MERIS) are available on-line, and Figure 9 shows part of the Browse window.

Product ordering
The ordering service access is restricted to authorised users according to the Envisat

Distribution Policy. Users may order existing and future products, but each order needs to be validated with respect to:

- the user profile (class, priority, quota)
- the order requests previously planned
- the mission and instrument constraints.

The Order Desk might therefore propose alternatives in the event of a conflict with existing requests. Order requests are used by both the Payload Data Segment and the FOS to build up the mission-operations plan. Users can check the status of their own orders on-line at any time.

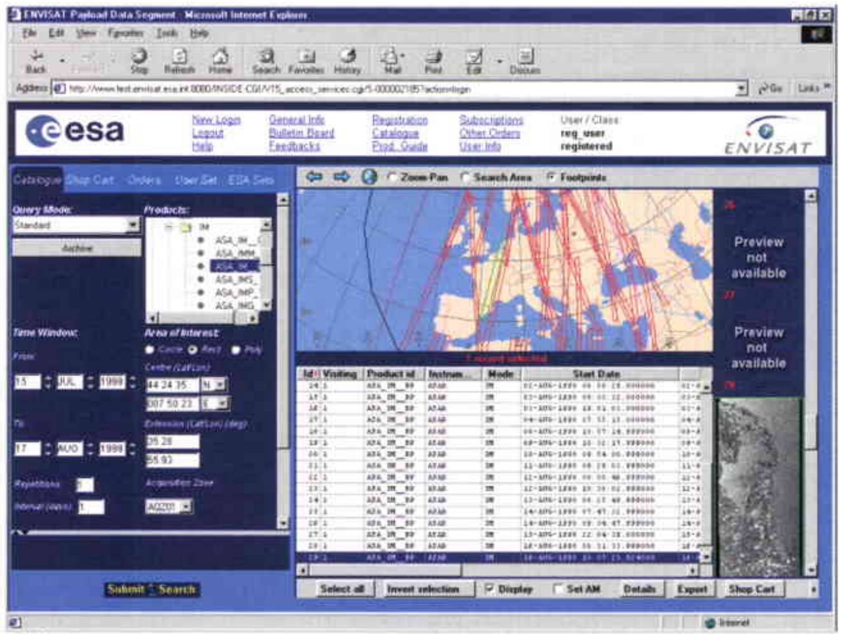

Figure 8. The USF interactive user interface based on the EOLI applet

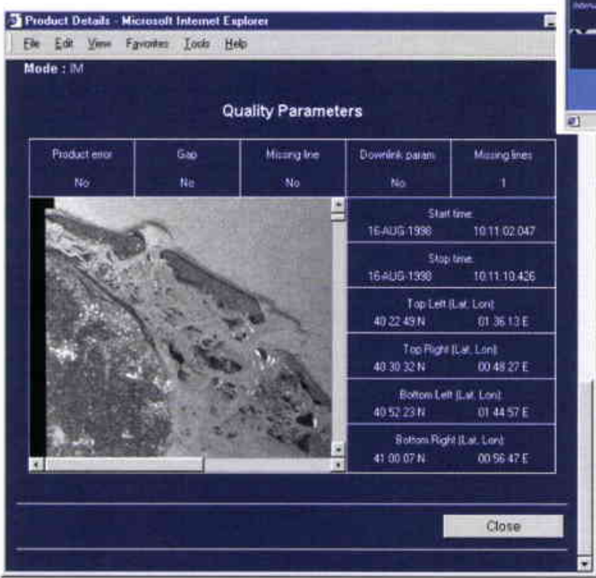

Figure 9. An Envisat Browse image

Child products

In addition to full products, users may order a subset of existing products, so-called 'Child Products'. The aim of this function is to reduce the product's size in order to ease its distribution. A full product may be too large for a user to download, while a subset of it could be downloaded easily. This is a very flexible approach, as the user can define child products from an existing product stored in one of the PDS archive facilities, specifying any combination of child extraction parameters: time, band, star name, or data set. For example, instead of ordering a full Level-1 MERIS product (e.g. MERIS geo-located and calibrated TOA radiance), a user may also request the extraction of just a few of the 15 bands and for a shorter time window. An example is shown in Figure 10.

Scene products

The user may also request the extraction of scenes from a larger strip-line product (AATSR, ASAR and MERIS Level-1b and -2). Such a request can be made for future products as well as for existing archived products. The size of a scene is pre-defined and depends on the product type, and the scene may be located anywhere along-track for the three imagers. The scene always has the same width as the original AATSR or ASAR product. The MERIS scenes that can be ordered are square in format (287 x 287 km^2 quarter or 575 x 575 km^2 half scenes). The user can specify the location of a MERIS full-resolution scene across-track within the product boundaries.

Other orders

In addition to the above data products, users may also order software tools (e.g. product handling and visualisation, and local inventory access tools), directory and guide update files, and inventory update files. This list is not exhaustive and will grow during the Envisat mission.

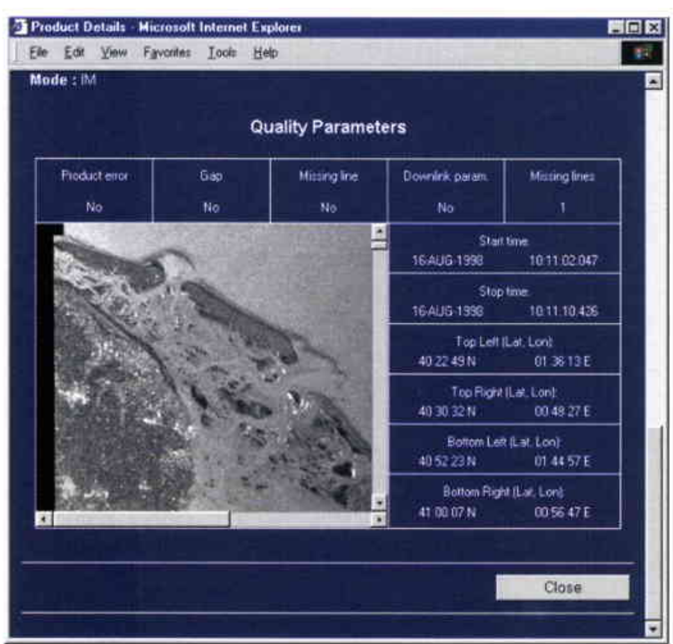

Figure 10. Child-product parameter specifications

Figure 11. Web mapping

User administration: registration and account information

There are two types of users: unregistered, without a personal account; and registered, with a personal account. Any user can be registered, and there is no fee for registration. A user can also have several accounts for different purposes. The account information contains various data on the user: personal data (e.g. name, address, telephone/fax/e-mail) and account data (e.g. user name, password, priority, quota). The user may access these account parameters at any time and may change some of them (e.g. personal data or password), whilst some others may only be changed by the Envisat User Services operators (e.g. quota, priority).

User Services status and possible evolution

Around fifty users have already tested the Envisat User Services during the first rehearsal exercise with Calibration/Validation Principal Investigators in November 2000. The facilities were subsequently upgraded based on their comments, collected after that rehearsal. The User Services were then opened up again in February 2001 for familiarisation purposes. The Calibration/Validation Principal Investigators may access the User Services before Envisat's launch to enter their product requests in order to prepare for the Commissioning Phase.

Already today there are some plans and on-going activities to improve the User Services, involving:

- improvement of the user interface following remarks from users
- integrating of the Envisat User Services with existing MUIS services
- multi-mission querying and ordering
- faster catalogue access
- making Envisat visible from non-ESA information systems worldwide
- incorporating the most recent features of MUIS EOLI, like web mapping and 3-D VRML (virtual-reality) visualisation of Browse image products. Web-mapping features allow the user to select the background thematic layers that best fit the missions/sensors being queried. This allows easier interpretation of the products visualised via the EOLI interface.

New ideas for improvements will doubtless emerge as the Envisat mission gets fully underway.

Acknowledgment

The work described in this article was performed by several technicians and engineers from both ESA and Industry. esa

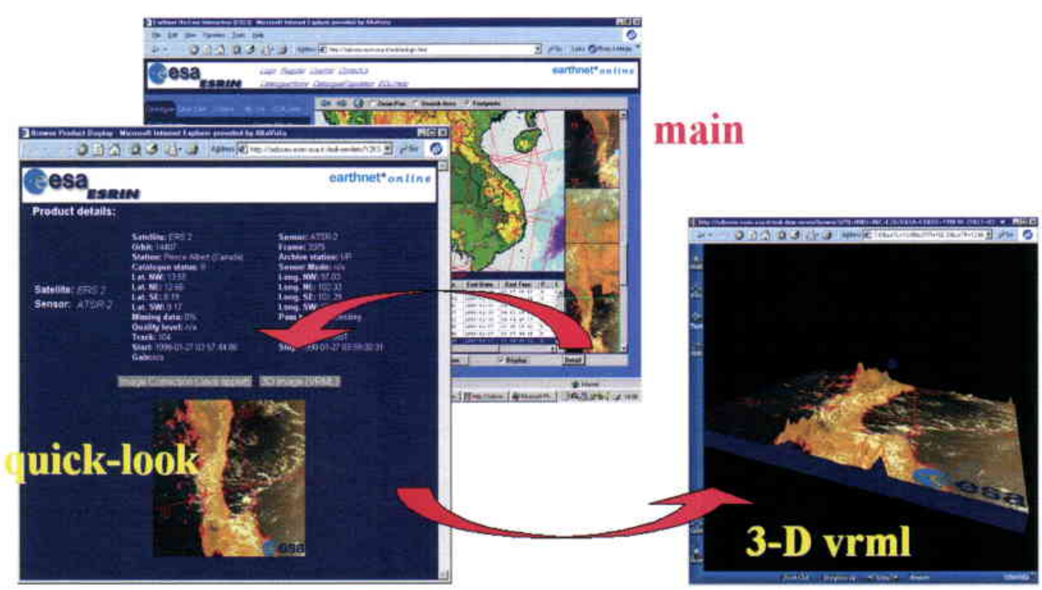

Figure 12. A 3-D VRML visualisation of a browse product

The Commissioning Phase and the Calibration/Validation Activities

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Envisat is designed to provide measurements of the atmosphere, ocean, land and ice over a five-year period. After the launch, a six-month Commissioning Phase is foreseen. This first period is dedicated to instrument switch-on and in-flight calibration and to the first validation of the Envisat products. There is general consensus that the calibration and especially the validation activities represent a long-term effort, which extends far beyond the duration of the Commissioning Phase and gradually shifts into algorithm improvement. The Commissioning Phase is the period that ESA has available to check out and verify the complete data chain (instruments and ground-processing algorithms) before releasing the Envisat data to the wide user community. At the end of the Commissioning Phase, the data quality is guaranteed by the Agency.

In addition to ESA and its industrial partners in the Envisat Consortium, many other companies and research institutes are contributing to the calibration and validation programme. A major contribution is being made by the Principal Investigators of approved proposals submitted to ESA in response to the worldwide 'Announcement of Opportunity for the Exploitation of Envisat Data Products' issued in 1998. Teams have been formed in which the various participants are working side-by-side to achieve the ambitious calibration and validation programme objectives.

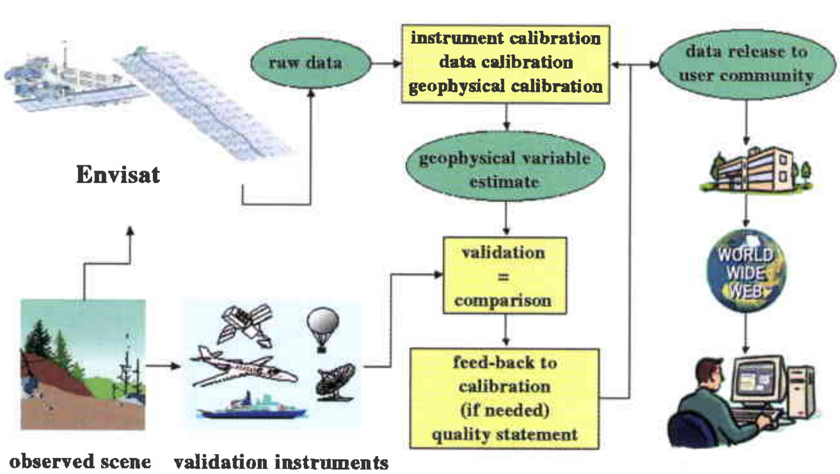


Figure 1. The Envisat calibration/validation concept

Calibration and validation defined

Following internationally agreed definitions, instrument and data calibration involves both pre-launch and post-launch measurements to fully characterise the payload instruments, and subsequent activities to configure the ground processors to provide calibrated (Level-1b) data products (e.g. radiance, reflectance, transmittance, radar backscattering coefficient, radar-echo time delay). Geophysical calibration and validation is a process whereby geophysical data products (Level-2) are derived from the Level-1 data products and checked against independent (in-situ) measurements of the relevant geophysical variables. These include atmospheric variables (temperature, pressure, atmospheric constituents, aerosol and cloud parameters), marine variables (ocean surface wind and waves, ocean colour, sea-surface temperature) and land variables (vegetation index, land surface temperature, pressure and reflectance). For each geophysical data product, a number of different in-situ measurements have to be made by ground-based, airborne and balloon-borne instruments. In addition, comparisons with other satellites and analyses based on data assimilation models will be made.

After the Commissioning Phase, the validation programme will make a quality assessment of the Envisat geophysical data products and will recommend re-calibration and algorithm development as appropriate. The overall concept of the process is illustrated in Figure 1.

Objectives, co-ordination and schedule

The Envisat Payload Data Segment (PDS) will routinely produce an unprecedented large number of products (both the Level-1b geo-located and calibrated engineering parameters, and the Level-2 geo-located geophysical products). ESA is committed to deliver products to the wide user community starting six months after launch, at the end of the

Commissioning Phase. Within this six-month period, the objective is to achieve full calibration of all Level-1b data products and a preliminary validation of the Level-2 products. In order to achieve this challenging objective, the following working teams have been formed:
- ASAR Calibration and Validation Team
- MERIS Calibration Team
- AATSR Calibration Team
- MERIS and AATSR Validation Team (MAVT)
- MIPAS Calibration and Algorithm Verification Team
- GOMOS Calibration and Algorithm Verification Team
- SCIAMACHY Calibration and Algorithm Verification Team
- Atmospheric Chemistry Validation Team (ACVT), responsible for validation of GOMOS, MIPAS and SCIAMACHY Level-2 products
- RA-2 Calibration Team
- RA-2/MWR Cross-Calibration and Validation Team (CCVT)
- Precise Orbit Determination Team (POD).

The necessary expertise is represented in the teams by ESA staff, the Expert Support Laboratories who designed the retrieval algorithms, some instrument contractor representatives (mainly in the calibration teams), and Principal Investigators leading the selected calibration/validation projects resulting from the Announcement of Opportunity.

The schedule for the initial calibration and validation activities is shown in Figure 2. The process starts just after launch with the switch-on of the different payload instruments. This phase has a limited duration and aims at verifying the functionality and operability of the various instruments from the ground. It will be completed at different times for the different instruments. As soon as the functional checkout of each instrument is completed, the calibration and validation activities will start for that instrument, consisting of three main components:
- Instrument in-flight calibration and Level-1b ground-processor verification.
- Level- 2 algorithm verification and data-product assessments.
- Geophysical campaigns and independent validation assessments.

These activities follow each other in a logical sequence. A calibrated and stable instrument configuration is required to properly assess the quality of the retrieval of the geophysical quantities, in order to avoid instrument biases and drifts being interpreted as geophysical signals. Some interdependency among these activities exists, as outlined in the schedule in Figure 2. At the beginning, the focus is on the in-flight calibration of the instrument and on its re-characterisation. This is followed by a first verification of the Level-1b processing chain.

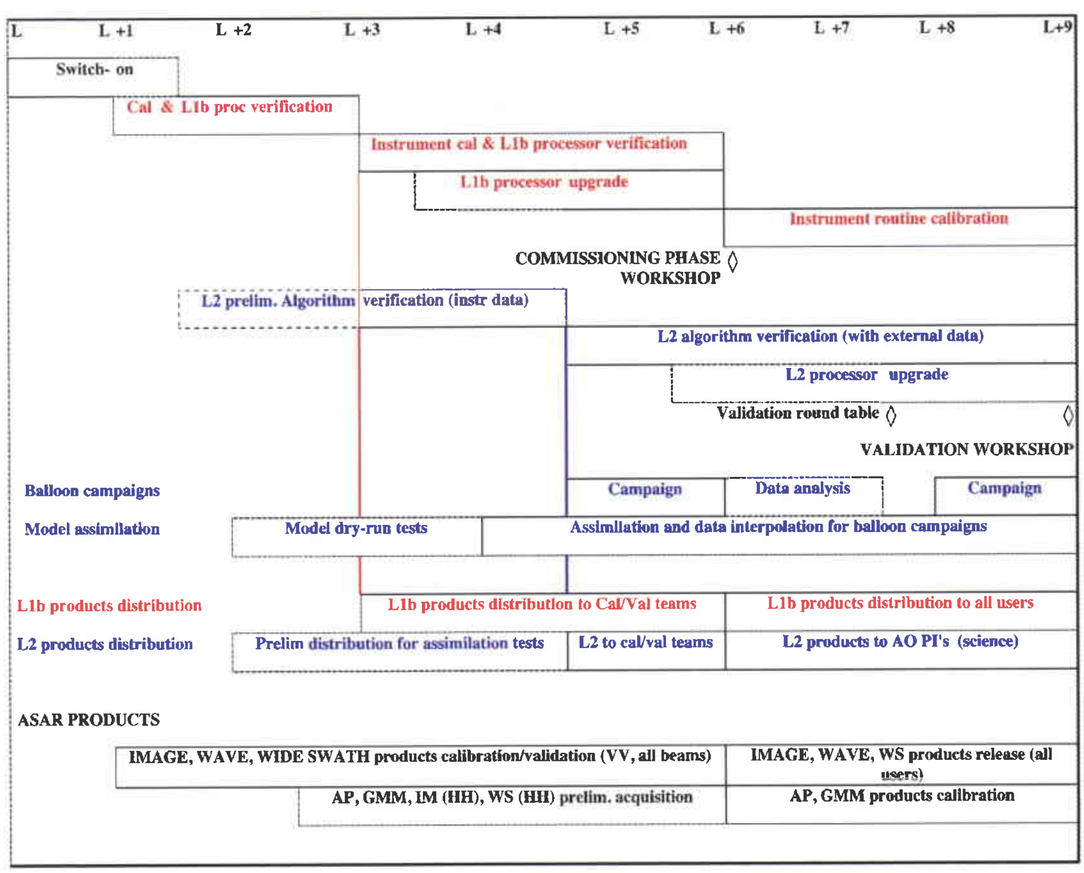


Figure 2. Schedule for the Envisat calibration/ validation activities and product release

Three months after launch, this phase will be completed and Level-1b data can be reliably used by the Investigators and ESLs working on the verification of the Level-2 processing chain. In the remaining three months, the parameters used in the Level-1b processing chain need to be adjusted following in-orbit characterisation of the payload instruments. It is anticipated that at the end of the Commissioning Phase the first upgrade of the Level-1b ground processor will take place. Reprocessing of the Level-1b data acquired during the Commissioning Phase is likely to be needed (as a consequence of the Commissioning-Phase activities and processor update) and can then be initiated. The routine calibration phase begins at launch + 6 months.

The Level-2 algorithm verification starts after the provision of the first Level-1b data at launch + 3 months. This will initially mainly consist of processor-behaviour checks based on the detailed analysis of the intermediate processing results on real data, and will not involve external data coming from geophysical campaigns. This activity is the first in-orbit verification of the pre-launch processor tests, which were based on a limited set of simulated data generated using highly sophisticated instrument simulators. After a few weeks of operation in orbit, an immense amount of real data will be available to verify the processor behaviour: It is expected that this data will reveal a lot of interesting features that might necessitate processor adjustments.

At launch + 4.5 months, the first phase of the Level-2 algorithm verification will be completed, the Level-2 products will be distributed to the whole validation community, and the geophysical validation campaigns will commence. The Level-2 algorithm verification can now benefit from external data from campaigns, model assimilation runs, and comparisons with other satellites' data. This activity extends beyond the end of the Commissioning Phase and culminates in the Validation Workshop, 9 months after the launch. The aim is to be able to assess the quality of the geophysical data by this time.

The validation activities will continue after the Workshop, with algorithm improvements in particular still taking place.

As shown in Figure 2, the schedule for the ASAR calibration/validation activities is slightly different because of the complexity of the instrument's calibration and the limited geophysical products derived from this instrument (only the Level-2 wind/wave product). The quality of a large number of ASAR products needs to be assessed. By the end of the Commissioning Phase, all ASAR products (VV polarisation, for all beams/incidence angles) derived from the Image Mode, from the Wave Mode and from the Wide-Swath Mode will be verified. Distribution of these products to the general user community will start as soon as each product has been successfully verified. The remaining ASAR products (Global Monitoring Mode and Alternating Polarisation Mode products) will be released no later than 9 months after launch.

Calibration activities

The calibration activities to be carried out in orbit consist of:

- platform calibration
- instrument calibration, and
- processor calibration.

The platform calibration relates to the verification and optimisation of parameters that control support functions for the payload, such as the characterisation of the orbit characteristics, of instrument pointing, and of the X-, Ka- and S-band communication links.

The performance of each of the individual instruments will be verified and the control parameters optimised. Of particular importance is the characterisation of the instrument response to temperature variations and ageing (instabilities and drifts). During the first weeks, periodic re-calibration of the instrument may be required. Most instruments have special operational modes for calibration and the data resulting from these have to be analysed. These data will be used to generate updated coefficients and tables for use in the ground processors.

The ground processors for the various instruments are part of the Payload Data Segment. The PDS is an operational production chain, designed to continuously handle a large amount of data. Each processor has been designed in a modular way, such that its configuration parameters are in an external file (auxiliary product) and may be changed. The processor settings will be optimised during the Commissioning Phase and subsequent changes will then be kept to a minimum in order to guarantee product continuity.

As part of the calibration activities, proper instrument control parameters have to be generated. The resulting instrument command tables will be sent to the Flight Operations Segment (FOS) to be used in the creation of the operational macro-commands to be uploaded to Envisat.

For the implementation of the above functions, dedicated hardware and software has been developed, independently of the operational data-processing chain, known as the Instrument Engineering Calibration Facility (IECF). The structure of the IECF provides the necessary flexibility; new algorithms can be added and existing ones may be modified and tested relatively quickly. The IECF will incorporate results from new analyses that will allow the calibration performance and product quality to be improved.

Validation activities

Since it is the objective of validation to compare the Envisat Level-2 data products routinely generated and archived within the Payload Data Segment with independent measurements of the relevant quantities, the validation activities consist of:

- organising data-acquisition campaigns for independent geophysical measurements
- setting up a facility for the collection, quality control and archiving of correlative data
- analysing correlative data in conjunction with Envisat data and formulating quality statements and recommendations for further work.

Figure 3. Launch of a balloon from Kiruna, in Sweden, for geophysical validation

Geophysical validation is far from a trivial problem. The requirements and the methods to be used were the subject of a long scientific debate, particularly for the atmospheric-chemistry instruments. Another complication has been the international nature of the exercise, with the participation of a large number of organisations, institutes and individual scientists. Therefore, a long preparation process was necessary. Currently, the campaign and analysis plans are defined and the various agreements and contracts are being finalised.

While all Envisat products will be stored in the PDS, all data from the various validation campaigns will be held in a central data-storage facility established at the Norwegian Institute for Air Research (NILU). NILU will provide access to correlative measurements from sensors on-board satellites, aircraft, balloons and ships, as well as from ground-based instruments and underwater devices and numerical models, such as that of the European Centre for Medium-range Weather Forecasting (ECMWF). This facility will be particularly relevant to the atmospheric-chemistry sensors and to MERIS. Two types of data will be stored in the NILU database, fixed-point and transect data. The latter will only be provided for inclusion in the database for selected times that correspond to the satellite overpasses. All data provided to NILU for inclusion in the database will be in HDF v4.1 r3 format. Envisat data will not be stored in the NILU database, but will be accessible via the PDS.

The first analysis of the Level-2 data products has to be done in a short time. The requirement is to arrive at a preliminary quality assessment 9 months after launch, at the time of the Validation Workshop. In some cases, there will be very limited time available for comparisons between validation-campaign data and Envisat data (Fig. 2). However, the time pressure comes from the requirement to establish confidence in the new data products as soon as possible, as this is a prerequisite for applications development and data exploitation.

Pre-launch preparations

It follows from the previous paragraphs that a large amount of preparatory work is required to achieve the calibration and validation goals. Obviously, the in-orbit programme relies on the successful completion of all pre-launch instrument and platform testing, as well as the development work on the ground segment. In addition, major efforts were necessary by ESA, as well as the supporting institutes and scientists, to develop software tools for analysing Envisat data products in a relatively short time.

In addition to the development of analysis tools, dedicated devices were developed for calibration, such as radar transponders, and for validation, such as airborne equipment and atmospheric lidars. Fortunately, in the latter case the Envisat project could benefit in many instances from the development of instrumentation during the last few years in the framework of scientific campaigns not directly related to Envisat. In view of the time pressure on the calibration and validation, detailed procedures have been established for the various teams, down to the individual assignments, the tools to be used, the pass/fail criteria, the detailed schedule, and the interactions between the different players.

Well in advance of the launch, a series of rehearsal exercises involving all facilities (NILU, IECF, PDS) and tools are scheduled to test the procedures, communication and analysis methods. These will facilitate remedial actions where required. These rehearsal exercises are supported by simulated Envisat products.

Calibration and validation activities for individual instruments

ASAR

The ASAR instrument calibration concept is built on the well-established methodology developed for ERS. It is based on measurements acquired over precision calibration transponders deployed in the Netherlands for absolute calibration, and over the Amazonian rain forest for antenna-pattern characterisation. In addition, a special calibration subsystem onboard will support the in-flight instrument characterisation and facilitate the monitoring of any gain variations in the active antenna. Needless to say, this task is more of a challenge for ASAR than it was for ERS because ASAR has a total of eight beams, five different operational modes and up to four polarisation combinations.

The validation of ASAR's Level-2 wind/wave product will involve local comparisons with in-situ measurements and global comparison through assimilation of Envisat data into numerical weather-prediction models.

MERIS

The in-flight instrument calibration of MERIS will use the onboard sunlit calibration diffuser plates. These have been characterised, using a dedicated optical bench, to an absolute accuracy of better than 1%. A round-robin exercise (involving NASA) will ensure consistency of BRDF measurements at various laboratories and consequently will provide traceability across different missions.

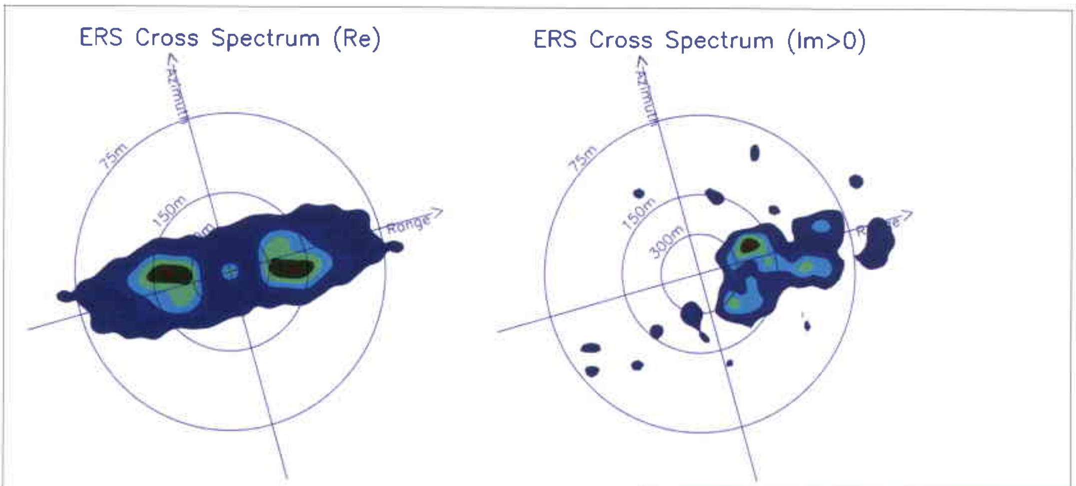
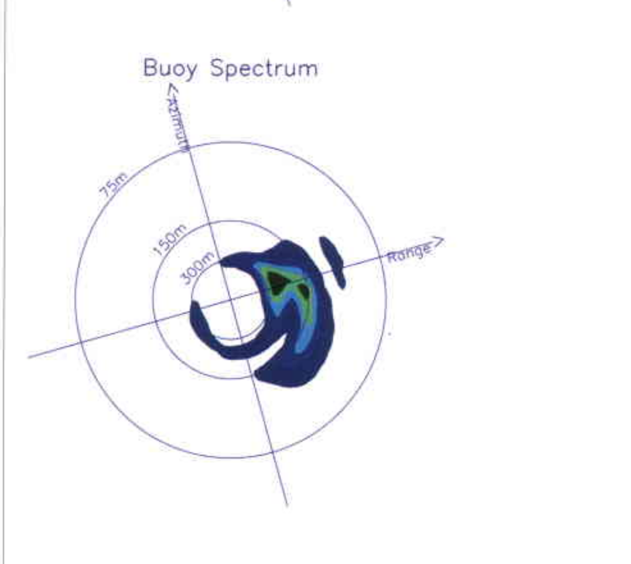



Figure 4. Simulated ASAR wave product based on ERS data

Figure 5. A SAR calibration transponder

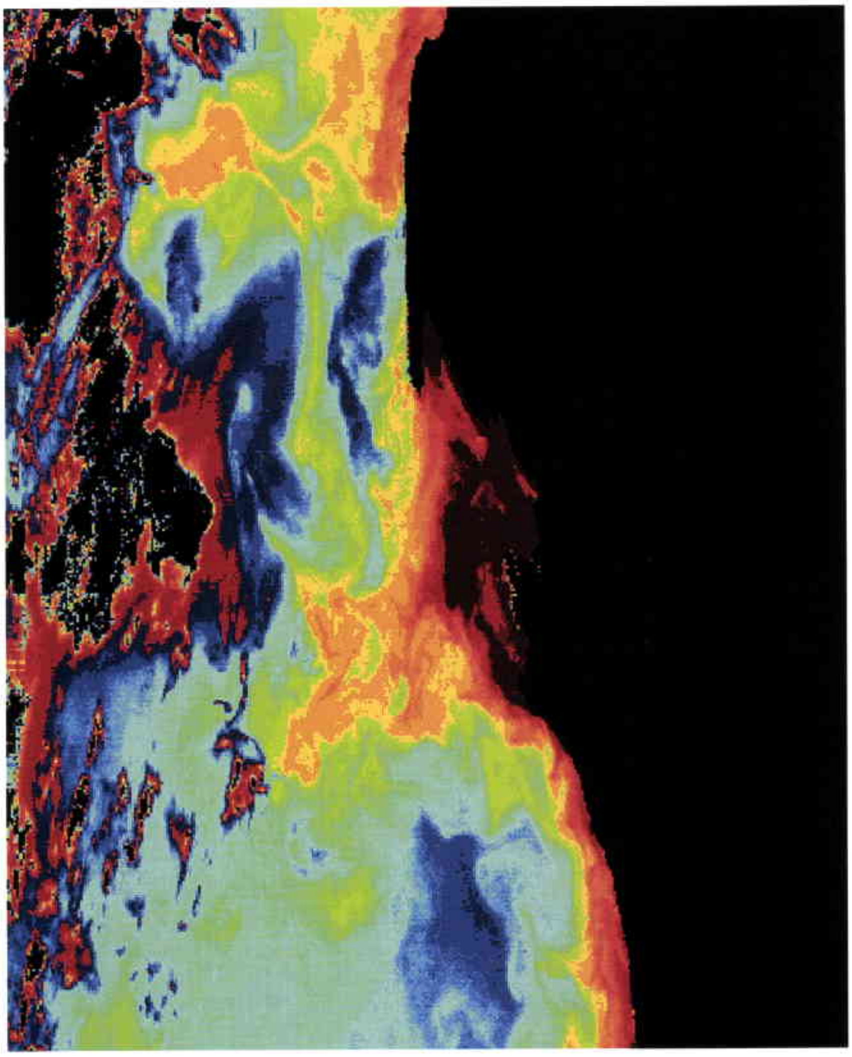


Figure 6. SeaWiFs Level-2C chlorophyll product for an area south of the Canary Islands, off the west coast of Africa

Validation of Top of the Atmosphere (TOA) radiances measured by MERIS will be achieved by comparison with TOA radiance values determined through a number of vicarious calibration methods:
- simultaneous in-situ measurements of natural targets
- analysis of Rayleigh scattering over clear water
- analysis of Sun glint
- data acquisition over stable deserts sites; the BRDF of these sites has been initially characterised using field equipment complemented by bi-directional TOA measurements from several spaceborne sensors
- simultaneous acquisition by other sensors.

Proposals to validate MERIS ocean-colour products for open ocean and coastal waters involve the installation of optical buoys, in-situ data collection during research cruises, and instrumentation on-board third-party vessels.

AATSR

AATSR is a self-calibrating instrument. It has an on-board calibration system, which involves the use of two specially designed and highly stable blackbody reference targets (for the thermal channels), and a diffusely reflecting target that is illuminated once per orbit (for the visible and near-infrared channels). Calibration of the instrument, as such, after launch is not required. There will, however, be specific activities to check and characterise the instrument post-launch, plus algorithm verification whereby the data-processing algorithms are verified and fine-tuned.

The core validation programme for AATSR has the following aims:
- to determine whether the AATSR instrument is returning an acceptable global skin sea-surface temperature (SSST ± 0.3 K)
- to make an initial assessment of the quality of the AATSR SST data products at a limited number of international sites during different seasons; making timely use of any tandem ATSR-2/AATSR mission will facilitate the determination of any bias between their measurements (and AVHRR).

The core validation activities for SST fall under three measurement types:
- *Broad Scale*: comparison with SST analysis fields, and the systematic review of buoy data.

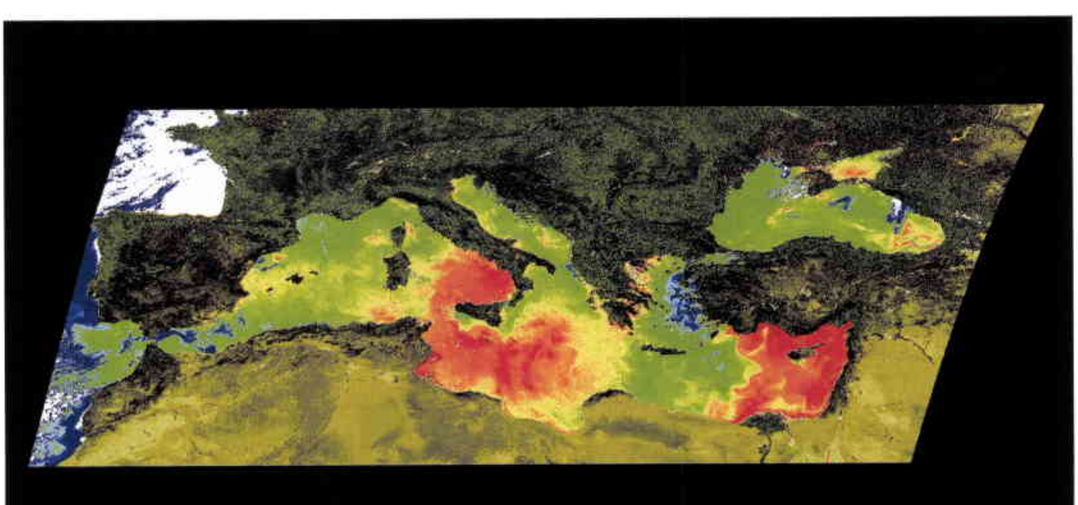


Figure 7. Daytime sea-surface temperature of the Mediterranean in August 1997 from ATSR data

- *Moderate Accuracy*: autonomous measurements on ships of opportunity.
- *High Accuracy:* precision measurements.

Atmospheric-chemistry instruments
Calibration and validation requirements for the atmospheric-chemistry calibration and validation teams relate to both Level-1 products (transmittance, irradiances, radiances, reflectances and polarisation measurements) and Level-2 products (trace-gas columns and profiles, aerosol and cloud detection). Correlative measurements will be acquired by ground-based and sonde instruments, balloon sensors, aircraft sensors and through comparison with other satellite data. Activities involving algorithm verification are also to be carried out. In addition to the campaigns and field measurement comparison (generally characterised by a high accuracy, but restricted to single points), validation analyses will strongly benefit from the use of assimilation models. These models combine localised ingestion of actual observations with knowledge of the dynamics of the atmosphere, and allow the estimation of concentrations at locations and/or times where no observations are available. Whilst all three atmospheric-chemistry instruments aboard Envisat measure overlapping sets of trace-gas species, inter-comparisons between the sensors will initially be used for the identification of large deviations and consistency checking, and not for accuracy assessment or algorithm tuning.

The calibration and validation activities relating to the atmospheric-chemistry instruments are organised within seven working groups:

- three instrument-specific subgroups, responsible for the in-flight instrument calibration and for the verification of the Level-1b and Level-2 processors
- four subgroups (which are non-instrument-specific and are organised according to validation technique) that will perform associated validation activities.

The validation groups will use a combination of different techniques to validate the instruments both globally and at single locations. Several sites located at various latitudes have been selected for aircraft and balloon campaigns. Measurements of atmospheric constituents will be performed during several seasons, by means of large balloons, small balloons and high-altitude aircraft.

The aim of data-assimilation techniques is the combination of theoretical models and sparse measurements for the forecasting or analysis of the state of the atmosphere. The assimilation efforts will be organised into two main activities:

- *Assimilations into Numerical Weather Prediction (NWP) Models:* these will be performed by operational meteorological entities such as the European Centre for Medium-range Weather Forecasting (ECMWF) and others.
- *Assimilations into Chemical Transport Models (CTM):* these are applied more in a research mode and, contrary to the NWP models, do represent the details of the atmospheric chemistry.

Networks of ground-based instruments and sonde launch sites will provide a suite of correlative measurements covering a wide range of geophysical conditions. The aim is to generate a large number of data sets for inter-comparison with GOMOS, MIPAS and SCIAMACHY Level-2 products. A large number of different measurement instruments and techniques will be used, including lidars, spectrometers and radiometers.

Figure 8. The Russian high-altitude M-55 aircraft considered for validation campaigns

Figure 9. A Brewer spectrophotometer

RA-2 and MWR

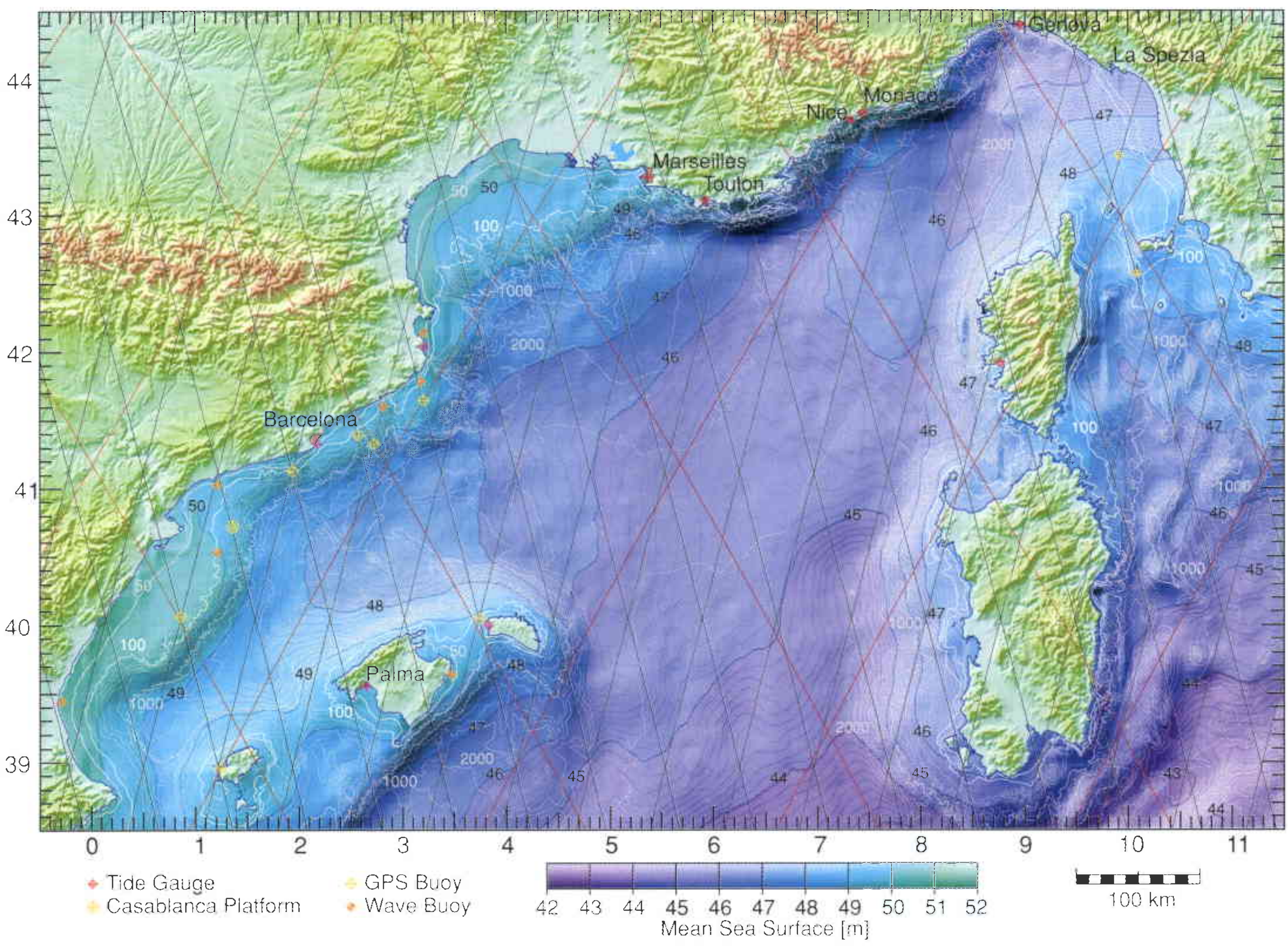
The RA-2 altimeter is intended to contribute to the continuation of an uninterrupted series of sea-level and ice-sheet elevation measurements that was started with ERS-1 in 1991. To fully exploit these measurements, it is necessary to determine the range bias and drift of the instrument, both to provide an absolute reference for the time series and to distinguish between instrumental artefacts and significant geophysical signals. To satisfy these needs, the required accuracy for the absolute range calibration is 1 cm for the bias and 1 mm/year for the drift. An experiment has been designed to achieve this effectively by making use of the northwestern Mediterranean Basin as a reference surface (Fig. 10).

Measurement of the vertical-incidence backscatter coefficient, sigma-0, by radar altimeters has largely been used for the determination of wind-speed over the ocean. The models applied are empirical and so it has been sufficient to perform relative calibration between missions. These are traced back to GEOS-3 and it is shown that there is an uncertainty in the absolute calibration of sigma-0, for all altimeters, of more than 1 dB. Recently, new applications of the altimeter sigma-0 measurement have been proposed, such as physically based models of sea-state bias and wave period, which require an absolute measure of sigma-0 to an accuracy of 0.2 dB. In response to this requirement, a plan for the absolute calibration of the RA-2 sigma-0 has been developed. By relative calibration, this absolute calibration may then be extended to all other altimeters. The measurement technique makes use of a dedicated transponder (developed by ESA). Acquisition of individual echoes (special RA-2 mode without onboard pre-averaging) will be commanded over the transponder.

The objectives of the Envisat RA-2 and MWR cross-calibration and validation are:

- Geophysical processing algorithm verification: verify algorithms, tune processing parameters.
- Validation of RA-2/MWR near-real-time and off-line products: validate parameters in the geophysical data record and estimate their accuracy.
- Relate calibration coefficients (bias and slope) with error estimates against ERS-2 and other altimetric missions of the three main measured parameters – range/height

Figure 10. The northwestern Mediterranean Basin used as reference surface for the Radar Altimeter absolute range calibration (the Envisat ground tracks are shown)



wave height and sigma-0/wind.
- Validation of the absolute sigma-0 (absolutely calibrated via transponder).
- Validation of MWR brightness temperatures and water vapour by comparison with in-situ measurements and with ERS MWR.
- Long-term drift detection.

Inter-calibration, or so-called 'cross-calibration', is the determination of relative biases between the measurements of different altimeters. Two altimetric systems will be compared through their global geophysical data products. The strength of the technique lies in the huge number of globally distributed measurements processed. The permanent tide-gauge network will provide an estimation of drift that is complementary to the relative bias obtained from cross-calibration based on altimetry alone. Relative calibration will unify the ERS and Envisat data sets. A relative calibration between ERS-2 and ERS-1 was performed during the ERS-2 Commissioning Phase. Relative biases between Envisat and Jason, Topex/Poseidon and Geosat Follow-On will also be estimated.

The Microwave Radiometer (MWR) will be verified by monitoring temperature and gain variation, and radiometric count range. The parameters to be calibrated are the brightness temperature of each channel, the wet tropospheric Altimeter path delay, and water vapour and liquid-water content. This will be done by:
- comparison with shipborne radiosondes
- comparison with coincident simulated brightness temperature from ECMWF meteorological fields
- comparison with other radiometers, and especially with the ERS-2 MWR.

Precise Orbit Determination (POD)
ESA will produce several types of satellite orbits for Envisat depending on the information available at the time of the orbit determination. Obviously, the predicted orbit information available prior to the actual data take is less accurate than the so-called 'restituted orbit' derived afterwards taking into account actual flight parameters. Orbit determination based on the measurements made by the DORIS instrument is even more precise. The intention is to nominally have these DORIS orbits in, respectively, the Fast Delivery Products, the Interim Geophysical Data Products (IGDPs) and the Geophysical Data Products (GDPs), which are composed of the corrected measurements of the Altimeter and Microwave Radiometer instruments. A POD Working Team has been formed which will compute and check the orbits operationally, and external experts will validate the orbit system and products. Activities to conduct the orbit verification will include three important tasks:
- pre-launch verification of the POD project orbit software and procedures
- assessment of POD models and standards
- post-launch orbit accuracy validation and verification.

ERS-1/2 and Topex/Poseidon have provided opportunities for geodesists to develop the so-called 'short-arc techniques' that are based on a geometric evaluation of the orbits using data from dense satellite laser-ranging networks. This also is a task of the POD team and will prove very useful for the Mediterranean area, where extensive calibration and validation activities will be performed.

Conclusions
The approach to the calibration of the Envisat Instruments, to the verification of the on-ground processing chains, and to the validation of the Envisat-derived geophysical quantities has been presented. The Agency is committed to deliver the Envisat data to the general user community starting six months after the satellite's launch. The calibration and validation activities have been organised in order to achieve this objective. The size and the complexity of the mission represent a major challenge to all involved.

Acknowledgements
This article is based on the Envisat Calibration and Validation Plan, compiled by the calibration and validation teams. This document is available on the ESA Envisat web site in PDF format. For more information on Envisat, please visit http://envisat.esa.int.

Research Activities in Response to the Envisat Announcement of Opportunity

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Since the launch of ERS-1 in 1991, ESA has issued several Announcements of Opportunity (AOs) for scientific research and application development using ERS satellite data. A total of more than 1000 projects proposed by scientific investigators from around the world have been selected and accepted. The outcomes of the various AO projects have been presented at ESA-organised Symposia and Workshops and published in the scientific literature. The Envisat AO, issued in December 1997, led to the selection of 674 proposals in support of scientific research, application development and calibration and validation. This is the largest and most diverse AO ever issued by ESA in the Earth-observation field.

Introduction

Over the last ten years, ESA has released six Announcements of Opportunity to exploit ERS and now Envisat satellite data, with the goal of fostering scientific knowledge and our understanding of the Earth's environment. The primary objectives of all of the AOs were to support scientific research, stimulate the development of algorithms and products, and to support application demonstrations. In addition, they facilitated the transfer of scientific results into sustainable applications/services and supported the transfer of technology. By signing the ESA Terms and Conditions, the project leaders of the accepted AO proposals agreed to generate regular reports on their project's progress. As a result, the achievements of the ERS-1 and ERS-2 mission projects have been published in more than 8000 papers or articles (Fig. 1), covering all of the Earth-sciences disciplines.

* SERCO SpA support to ESRIN

The exciting results provided from past AOs, together with Envisat mission's ability to make significant contributions to environmental studies, generated a massive response to the first Envisat AO. The new sensors onboard Envisat will, in fact, open new perspectives for research dealing with atmospheric chemistry (GOMOS, MIPAS, SCIAMACHY) ocean colour and marine biology (MERIS), and will consolidate ongoing research in all of the other scientific disciplines, ensuring continuity with the ERS observations. The overview of worldwide participation in the ERS and Envisat AOs in Figure 2, shows that the number of accepted Envisat projects is more than double those for the third ERS AO.

The Envisat Announcement of Opportunity

In October 1998, the results of the review of the 734 proposals submitted in response to the

Figure 1. Striking results from the use of ERS-1/ERS-2 data

first Envisat AO were presented to the ESA Earth Observation Programme Board, formalising the final acceptance of 674 proposals (the list of accepted proposals is available on the Web at http://esa-ao.org/accepted.pdf)

Proposals had been submitted from more than 40 different countries, covering the three main categories defined in the AO, namely:

- Scientific Research
- Application Development and Demonstration
- Calibration and Geophysical Validation of Envisat Data Products.

The division of the accepted proposals into these categories reveals that the large majority (64%) fall within the scientific domain, 18% address the calibration and validation of Envisat products, and 18% deal with application development and demonstration. The majority of the proposals (70%) originate from ESA Member States (Fig. 3), but with noticeably strong participation from several other countries: the USA (87 proposals), Canada (23 proposals), and Asia (51 proposals).

The interdisciplinary character of the Envisat mission is highlighted by the Earth-sciences disciplines identified in the AO proposals in Figure 4. For example, its data will be extensively used in studies dealing with oceanography, the atmosphere, renewable resources, and environmental hazards.

In the past, the traditional Earth sciences have tended to treat questions related to environmental monitoring as separate disciplines using only one type of data. The Envisat mission will provide global and synoptic observations of different kinds of processes at different spatial and spectral resolutions at exactly the same time. This will enable researchers to identify, characterise and monitor a wide range of environmental phenomena better than ever before, and it will provide the opportunity for geophysical-validation activities. An example of simultaneous coverage by ASAR, AATSR and MERIS is shown in Figure 5.

From a preliminary statistical analysis of the data requirements of the accepted Envisat AO scientific projects, it is clear that the synergistic use of sensors will be a main issue in the case of atmosphere, ocean, coastal-zone and land environment studies. In some projects related to coastal-zone and ocean monitoring, land applications and atmosphere, the synergistic use of data from up to six instruments is envisaged. As shown in Figure 6, specific clusterings of instruments can be identified in almost all of the application fields.

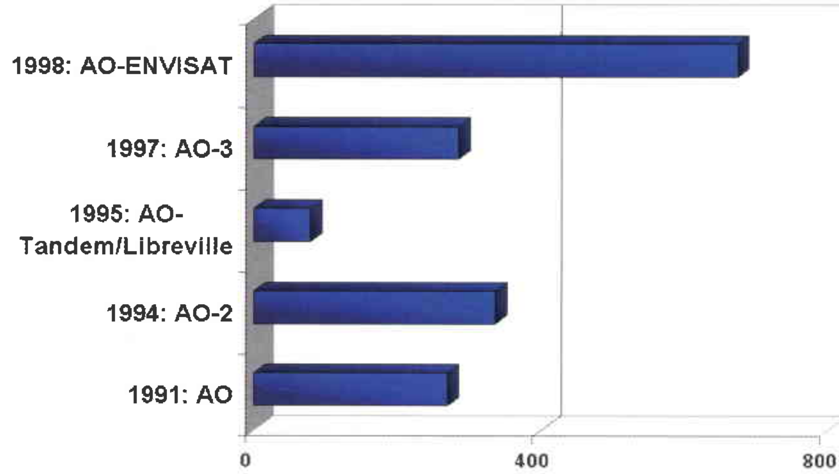


Figure 2. The acceptance statistics for the ERS and Envisat Announcements of Opportunity (AOs)

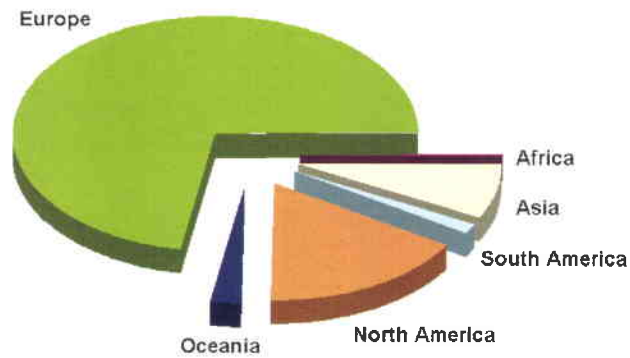


Figure 3. The geographical distribution of the accepted Envisat proposals

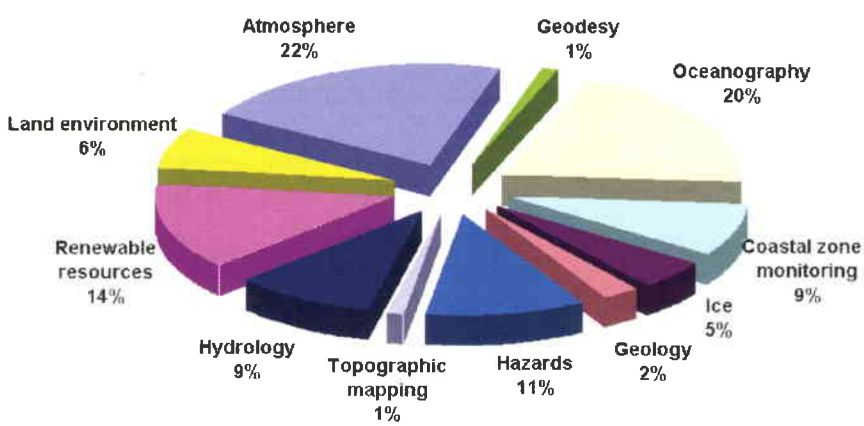


Figure 4. Thematic distribution of the accepted Envisat scientific projects

The number of scientific projects per two instrument sensor combination is shown in Table 1. For instance, three of Envisat's instruments, namely GOMOS, MIPAS, and SCIAMACHY, are dedicated to providing information on the chemical composition of the atmosphere and the concentration and distribution of greenhouse gases and aerosols. ERS provided several examples of synergies between different instruments; for example, by the combination of ATSR hot spots with GOME nitrogen-dioxide measurements, the local biomass-burning emission sources and the volume and dynamics of the emitted air pollution can be studied. The follow-on

Table 1. Scientific projects: number of projects per instrument combination

	ASAR	MERIS	AATSR	ASAR WAVE	RA2/MWR	MIPAS	GOMOS	SCIAMACHY	DORIS
ASAR	259								
MERIS	140	217							
AATSR	89	125	154						
ASAR WAVE	16	16	17	22					
RA-2/MWR	43	47	57	14	77				
MIPAS	5	11	11	0	4	59			
GOMOS	4	14	8	0	3	48	62		
SCIAMACHY	7	22	22	0	5	52	51	73	
DORIS	14	2	4	1	7	0	0	0	20

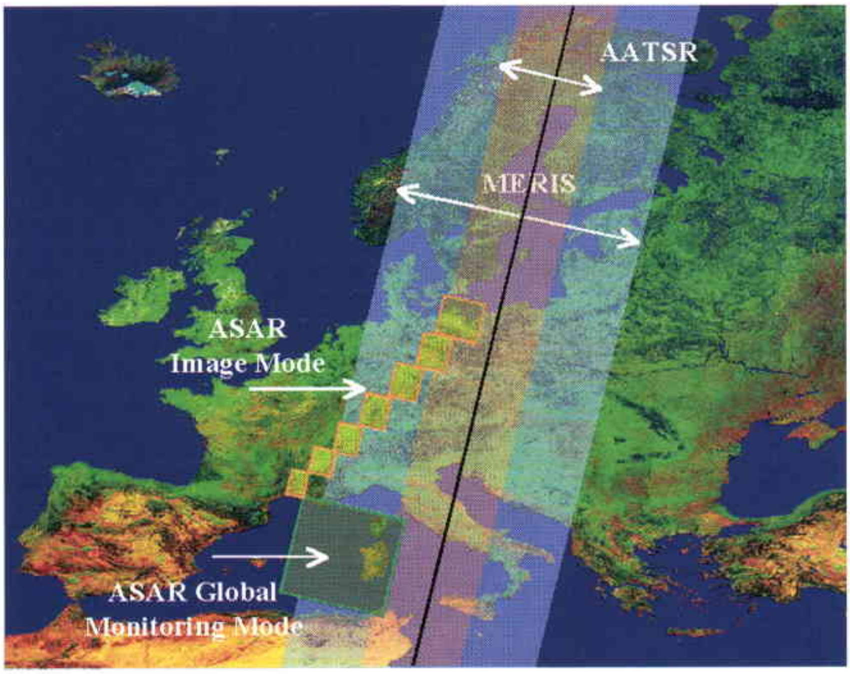


Figure 5. Synergistic observation capabilities of ASAR, MERIS and AATSR (with the satellite ground track in black)

instruments on Envisat – SCIAMACHY and AATSR – will provide the possibility to further develop their synergy, especially in terms of the derivation of new cloud/aerosol products (Fig. 7).

The synergistic use of sensors is envisaged in the case of oceanographic studies, such as MERIS, AATSR and RA-2/MWR, or the synergy between ASAR WAVE and RA2-MWR, which was successfully pioneered with ERS SAR WAVE and RA data. The provision of optical and microwave information taken simultaneously will benefit land studies, by improving land-use and land-cover classifications.

The monitoring of changes in environmental processes requires frequent repeat observations on regional to global scales. The succession of the two ERS missions and now Envisat (with its advanced and new

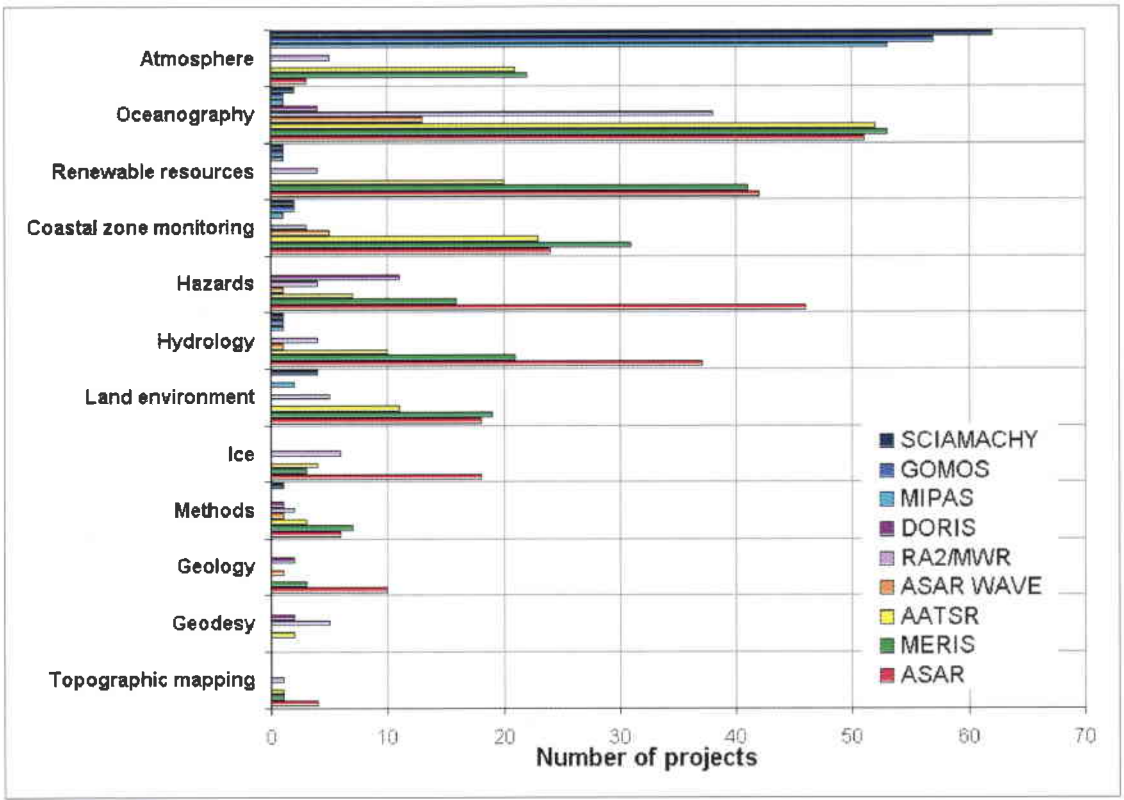


Figure 6. The scientific projects and their requested sensors

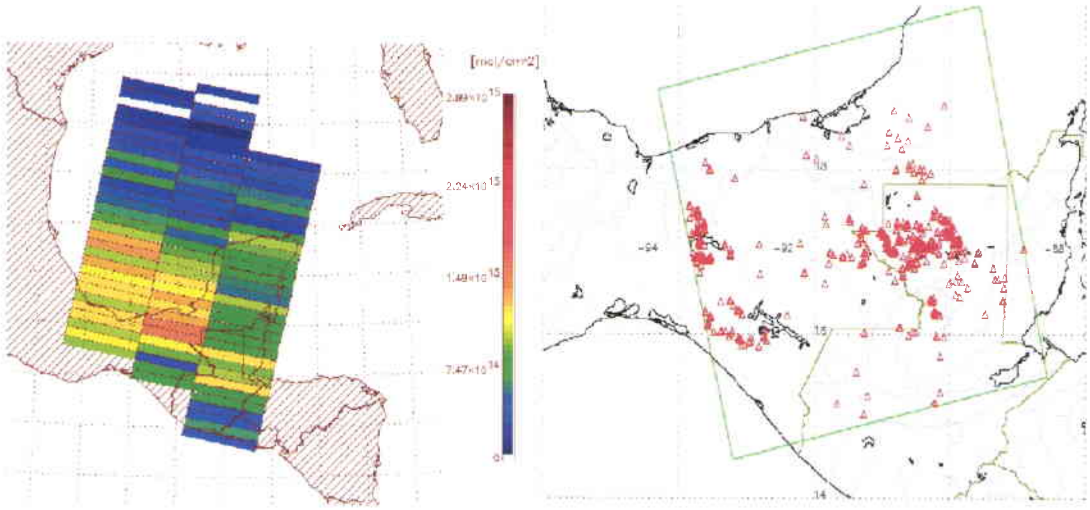


Figure 7. Forest fires in Mexico, monitored by instruments on-board ERS-2 to assess the extent and duration of the air pollution caused. Left: nitrogen-dioxide plume caused by biomass-burning over the Gulf of Mexico, measured by GOME on 13 May 1998. Right: ATSR-2 hot-spot measurements over Latin America on 13 May 1998 (Images processed at ESRIN)

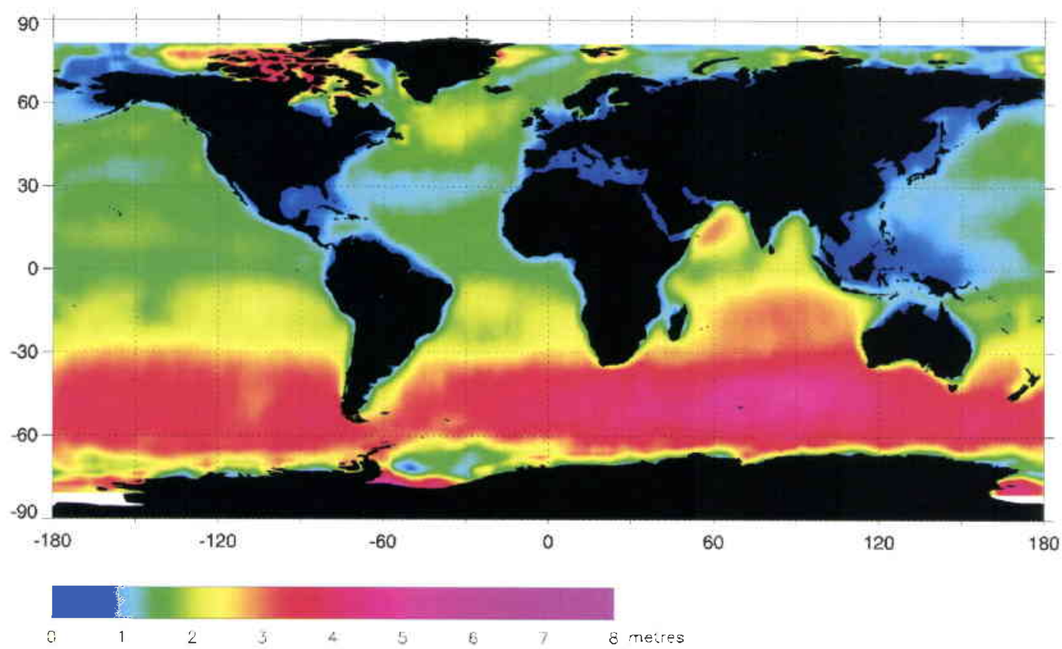
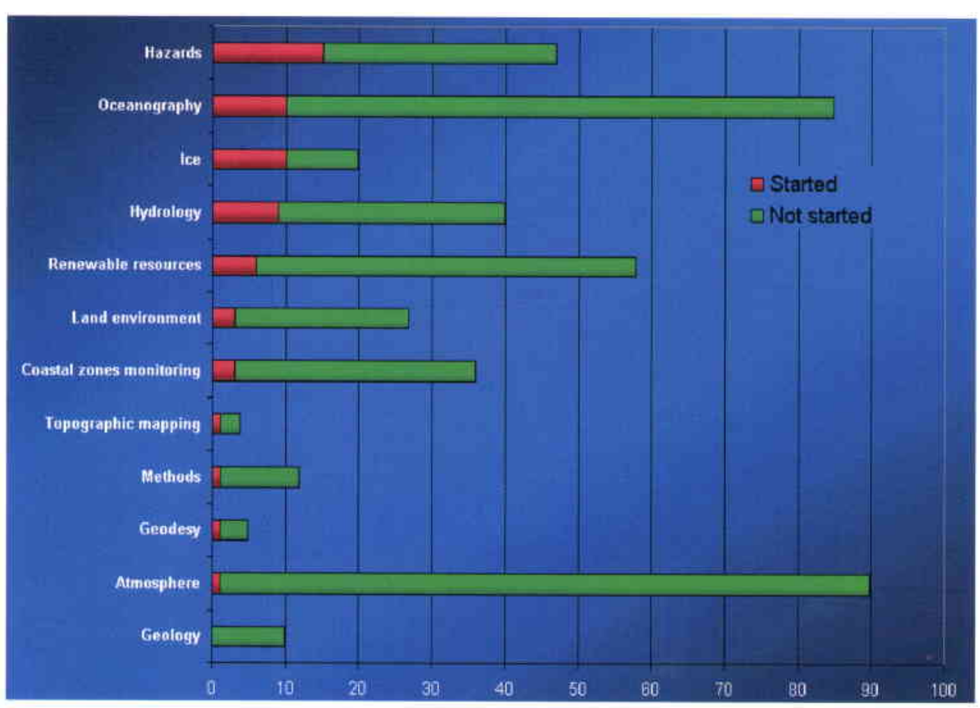


Figure 8. Map of Northern Hemisphere summer-averaged global significant wave heights from the ERS-2 Altimeter OPR final precision product. Note the high waves in the Roaring Forties and the Howling Fifties (southern winter). Seasonal mapping of the global wave field allows the monitoring of climatological trends (Image processed at ESRIN)

Figure 9. Envisat AO scientific projects already started



instruments) provides continuity of the observations relevant for oceans (Fig. 8), the cryosphere, land- and sea-surface temperatures, and ozone. Envisat products will permit the continuation of studies related to such processes as global warming, land-cover changes, and changes in the marine environment.

Data continuity is an issue for many projects: 38% of the accepted Envisat scientific projects plan to request ERS data, and to date 60 projects have already started using ERS data (Fig. 9).

Envisat will measure a large number of environmental parameters on local to global scales, and will offer new opportunities to obtain a comprehensive understanding of the

Earth as an integrated, dynamic system. The major research areas addressed by the scientific community in their proposals can be classified into the categories shown in Table 2.

Atmosphere

This category addresses the understanding of the chemical composition of, and the processes occurring in, the Earth's atmosphere. Measurements performed by Earth-observation satellites (in combination with ground-based measurements) during recent decades indicate two changes in the Earth's atmosphere: an increase in global average temperature and a decrease in global ozone concentration.

Human activities are believed to be responsible for these effects due to the emission of both greenhouse gases and chlorofluorocarbons (CFCs) into the atmosphere. Greenhouse gases (like water vapour, carbon dioxide and

Table 2. Breakdown of the Envisat scientific projects showing the different topics being studied, by main theme and sub-theme

Theme	Sub-theme
Atmosphere	• Atmospheric constituents: retrieval and geophysical results - 29 • Clouds, aerosols, surface parameters - 22 • UV radiation, Air pollution - 3 • Trend analysis, Assimilation - 21 • Chemistry models - 16
Oceanography	• Wind-waves - 6 • Primary production (Geochemistry, Fisheries, SST) - 25 • Ocean dynamics (Circulation, Sea-level, NRT) - 20 • Sea-features (Ship detection, Air-sea features) - 13 • Sea-ice - 17
Geodesy	• Geodesy - 5
Coastal-zone monitoring	• Bathymetry mapping - 2 • River discharge mapping - 7 • Coastal protection and change monitoring (algae blooms, erosion assessment, water pollution...) - 30
Ice	• Ice-sheet mapping - 5 • Ice-sheet dynamics - 15
Hydrology	• Snow melt - 8 • Soil moisture - 16 • Wetlands - 10 • Run-off - 4 • Water cycle - 2
Renewable resources	• Agriculture - 11 • Vegetation - 14 • Forestry - 16 • Land cover mapping - 17
Land environment	• Environment (Mapping, Urban, Climatology, Global change...) - 17 • Land surface temperature - 7 • Desertification - 3
Geology	• Geological mapping - 4 • Archaeology - 2
Hazards	• Earth motion (Subsidence, Crust motion) - 10 • Earthquakes - 14 • Volcanoes - 11 • Floods - 3 • Landslides and Soil erosion - 5 • Various hazards - 7
Topographic mapping	• DEM - 5
Methods	• Algorithm development, Software development, Product development, Validation -12

methane) allow short-wave radiation to enter, but block the outgoing long-wave radiation, thereby warming the air in the atmosphere. Such gases are produced by the burning of fossil fuels (coal, oil, and natural gas for heating and electricity; gasoline for transportation), deforestation, cattle ranching, and rice farming. Some of the impacts of global warming may include stronger storms, migration of agricultural zones, spreading of tropical diseases, melting of glaciers and ice caps and increases in pollution levels. CFCs (used for refrigeration, solvents, and aerosol propellant) stay in the atmosphere for a long time (e.g. CFC-11 ~50 years) and deplete the ozone in the stratosphere. When this occurs, the atmosphere's ability to block ultraviolet radiation is diminished. This UV radiation might have an impact on the human immune responses and could cause infectious diseases, the induction of skin cancers, particularly basal-cell carcinomas and melanoma, and eye diseases, especially cataracts. International protocols (Montreal 1987, Kyoto 1997) were signed by the leading industrial countries to reduce the emission of trace gases responsible for ozone destruction and global warming. Global measurements from satellites provide a very good means of monitoring them.

ERS AO projects using GOME measurements (Fig. 10) on the one hand enabled new research topics (e.g. trace-gas retrieval in the troposphere, improving insight into the variability of stratospheric ozone), and on the other developed the basis for such future applications as the monitoring of air pollution due to natural and industrial processes, and UV radiation monitoring to assess the impact of ozone depletion on human health and the weather.

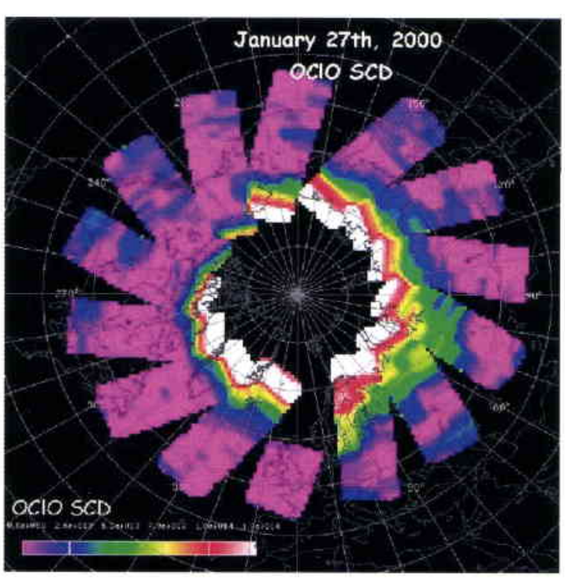
The Envisat atmospheric payload consisting of the GOMOS, MIPAS and SCIAMACHY instruments will measure a series of trace-gas constituents with new techniques, enabling a continuation and essential extension (e.g. retrieval of greenhouse gases, development of commercial services) of the work started on ERS with GOME.

Coastal zones, oceanography and geodesy

This segment is directed at improving the understanding of the complex marine dynamics and bio-geochemical cycles. The ocean is the major regulator of heat transfer on the planet (e.g. deep-water formation in the Arctic affects temperature differences between Europe and Canada) and so monitoring the ocean's circulation and its surface temperature is crucial for climate-trend monitoring. Climate change and its impact on Europe can be understood, and hence modelled and predicted, by monitoring the energy and latitudinal position of the Gulf stream and their trends.

Almost all living creatures in the oceans depend directly or indirectly on phytoplankton, which uses photosynthesis to convert light energy and raw materials (e.g. nitrogen, oxygen, water and carbon dioxide) into food ('primary production'). Since many countries depend on fish for food and commerce, understanding the processes that affect the ocean's primary production is important from both the economic and conservation viewpoints.

MERIS will provide a wealth of ocean-colour data and derived marine parameters which, when used in synergy with other geophysical parameters such as ocean currents (RA-2/MWR, DORIS), sea-surface temperatures (AATSR), or wind fields and wave spectra (RA-



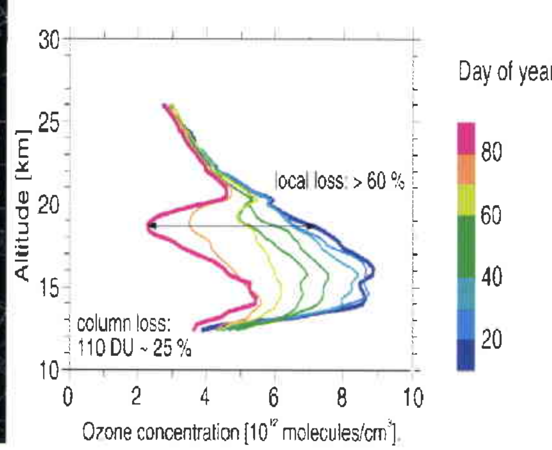


Figure 10. Left: Chlorine activation measured by the ERS GOME instrument over the Arctic on 27 January 2000 (Image courtesy of Univ. of Heidelberg). Right: Up to 60% ozone loss in the lower stratosphere in March 2000 over the Arctic (Image courtesy of NILU)

2/MWR, ASAR), provide a unique source from which a better understanding of the processes that determine the spatial and temporal distribution of biomass can be derived. Special emphasis is placed on the coastal zones, which are affected by intense and diverse activities with consequential environmental impacts for fishing, fish farming, industry of all types, release of sewage, pollution by trace metals and organic compounds, eutrophication by terrestrial fertilizers, tourism and marine traffic. Coastal waters are characterised by highly dynamic processes with complicated patterns of fronts and upwelling areas, rapid changes in concentrations of water constituents, and interactions between land and sea on a wide range of temporal and spatial scales. MERIS has been specifically designed for the mapping of concentrations of water constituents, notably suspended particulate matter, phytoplankton, and yellow substance.

Data obtained from the Radar Altimeter will offer the scientists working in the field of geodesy an opportunity to develop, test and refine models of the altimetric geoid and the Earth's gravity field. The Altimetry NRT service will be drastically improved for Envisat thanks to the development of high-quality algorithms for the NRT processor and of improved NRT orbit solution thanks to the on-board DORIS navigator. This will support international programmes to experiment with NRT oceanographic data assimilation for ocean forecasting.

The ERS AO projects have produced valuable results in terms of weather forecasting, detection and measurement of events such as the El Niño (Fig. 11), bathymetric applications, coastal-zone mapping, ship routing, ocean tides, assimilation of high-resolution data into regional models, and the extraction of parameters for information services like oil-spill detection, sea-ice monitoring or sea-state alarms.

Hydrology and ice

This segment studies the factors that control the global hydrologic cycle. Emphasis is placed on the reservoirs and fluxes of water, their coupling with plant life and biogeochemical cycles, and the definition of the impacts of modern agriculture and industry.

Extreme hydro-meteorological events such as storms, floods and droughts are a global threat to human life, infrastructure, water resources and the environment. Research work is directed to the effects of sea and land ice, run-off, and interactions between the vegetation, soil and topographic characteristics of the land surface and the components of the hydrologic cycle. With the novel tracking capabilities of Envisat's second-generation Altimeter, the levels of most of the Earth's rivers can be monitored with unprecedented accuracy.

ERS AO projects have allowed the grounding lines of glaciers to be defined and unprecedented ice-top and ice-velocity maps to be generated. Envisat will provide a new capability for the continued monitoring of ice caps and further mapping of areas such as Greenland and Antarctica.

Renewable resources, land environment and geology

For information needs related to changes in vegetation, de-forestation, desertification, wetlands, biomass-burning and greenhouse-gas reservoirs, the combination of the ASAR, MERIS and AATSR sensors constitutes a unique source of valuable information to support global and regional monitoring activities. Land-cover change will have an important influence on hydrology, global bio-geochemical cycles, and climate. Global estimates of the net flux of carbon due to land-

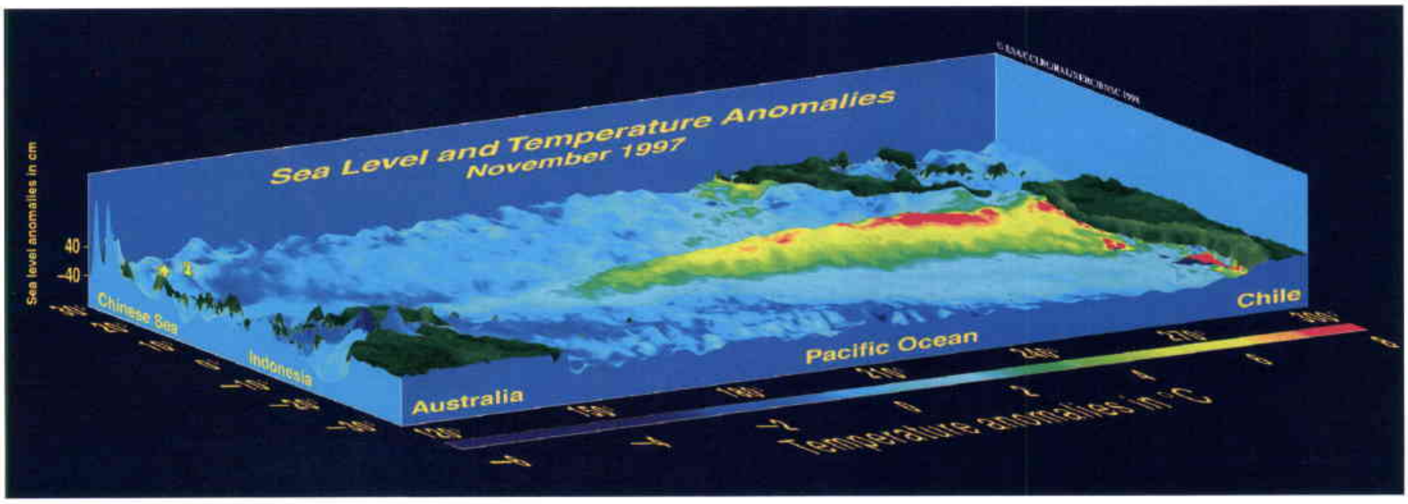


Figure 11. The El Niño has been monitored and studied with the sensors onboard the ERS missions (RA and ATSR). Envisat will pursue this monitoring to provide early detection and a better understanding of this phenomenon (Image processed at ESRIN)

cover change have been made in the last decade, yet the estimates for geologic and terrestrial biosphere carbon reservoirs are still not reliable enough to support an international policy. To develop a comprehensive analysis of green-house-gas emissions, land-cover and land-cover-change analyses will have to be coupled with efforts to obtain better ancillary data on carbon in vegetation and soils.

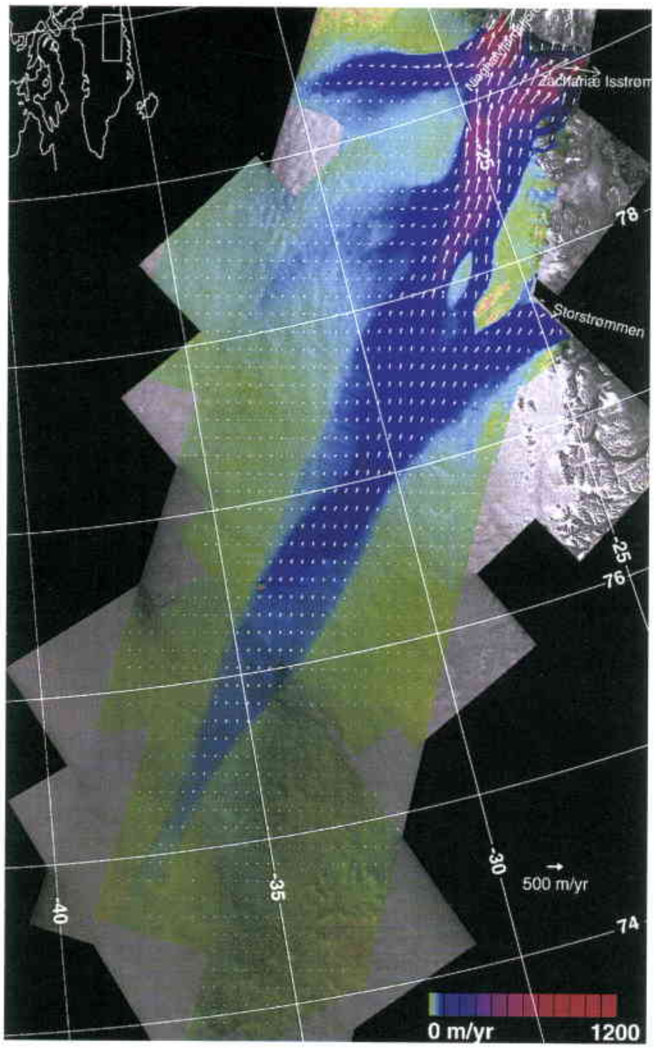


Figure 12. Ice-velocity mosaic of a Greenland glacier derived from ERS SAR interferometry (Image courtesy of Johan Mohr, DRCS)

Farmers trying to decide what crops to plant for the next season, urban planners shaping policy on the direction in which their city should grow, and emergency planning organisations charged with taking appropriate steps against floods or droughts, are just three of the groups that need better predictions of future conditions at the Earth's surface.

ERS data acquired as a result of the most recent AO were used for crop mapping (rice, cereals, sugar beet, etc.) and the derivation of area-based statistics, for the mapping of de-forestation, and for environmental studies. The higher incidence angles and dual-polarisation data from Envisat's ASAR (Fig. 13) will further improve the potential for forestry applications. Use of low incidence angles enhances the sensitivity to biomass, whereas the use of high incidence angles improves mapping of deforestation, and the dual polarisation will improve the discrimination of forest types.

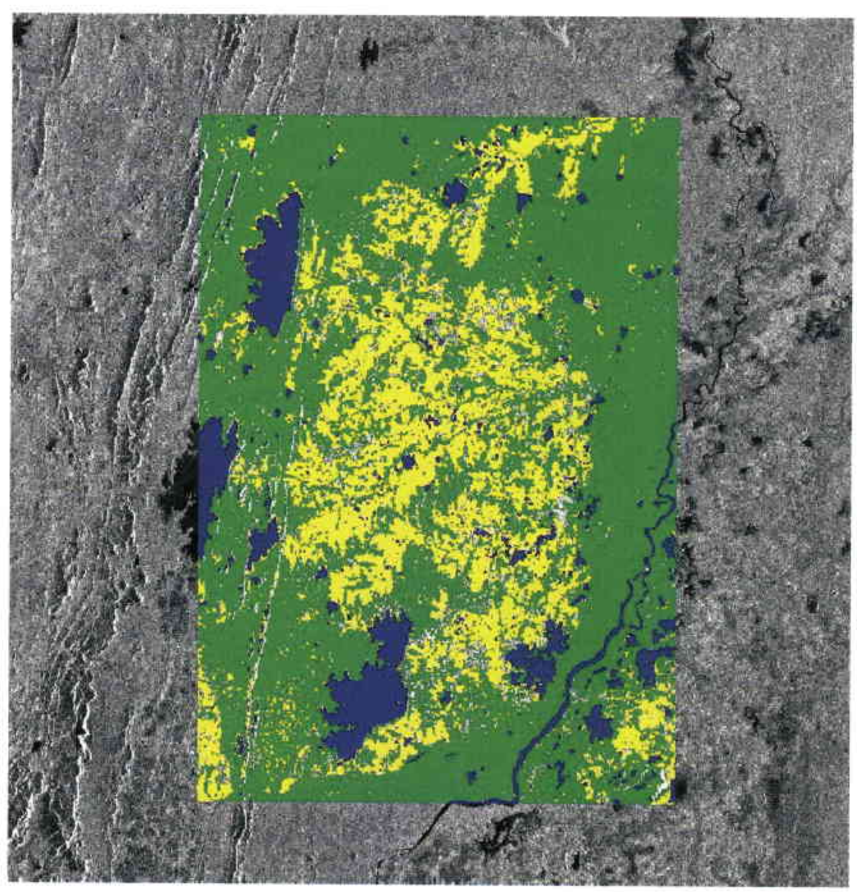


Figure 13. Map of rice fields (yellow) in Sri Lanka, derived from ERS SAR data. Envisat's ASAR, with its different viewing angles and polarisation capabilities, will allow further improvements and provide the possibility to obtain precise rice maps (Image courtesy of University of Zurich)

Another major issue of public concern and significant economic consequence is water management and water quality, whether for drinking purposes or ecological sustainability. Direct waste discharge, water abstraction, changes in land use, urbanisation, atmospheric pollution and, possibly, climate change all threaten to reduce the quality of this most vital resource. Envisat's data can provide base, topographic, and land-use maps for water-quality monitoring and hydrological modelling.

Hazards and topography

Hazard studies have received growing attention from the Earth-observation community in recent years due to the dramatic consequences of natural and man-made disasters for populations world-wide. Ecosystems are threatened by natural hazards such as floods, droughts, earthquakes, or wind storms, man-made pollutants resulting from

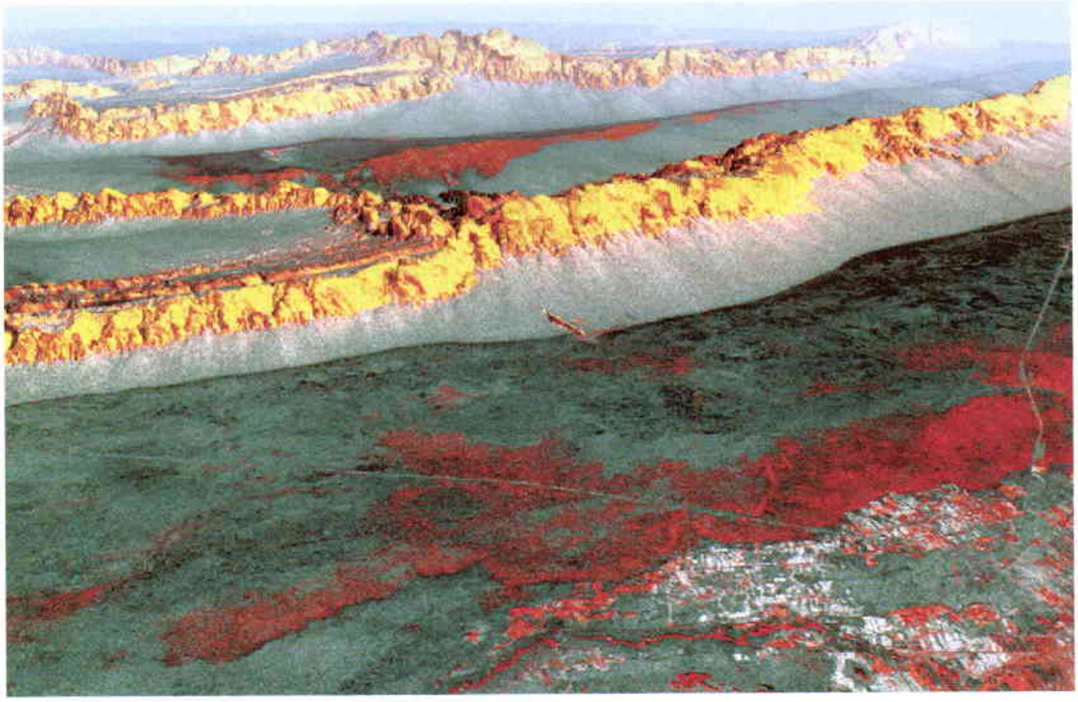


Figure 14. 3D image of the Bachu region, in western China, derived from ERS data. ASAR will provide similar images using the radargrammetry technique, combining data acquired at high and low incidence angles (Image courtesy of DLR)

waste discharges, and careless acts by man such as uncontrolled de-forestation leading to loss of bio-diversity. Research activities are directed at increasing the understanding of how episodic processes such as rainfall run-off, dust storms, volcanism, and earthquakes on the one hand, and human actions on the other, can have an impact on the Earth's surface.

The latest achievements of the AO projects are related to the refinement of InSAR techniques: very large active fault structures, such as the San Andreas fault, are being measured using ERS SAR interferometry; seismic deformations are being quantified; and some work has been done to monitor volcanic deformations and estimate the amount of magma contained in the chamber via comparison with theoretical models. The exploitation of interferometry for the quantification of land subsidence is almost operational, and new results could be obtained in terms of land-slide monitoring. The derivation of flood maps from SAR data is another almost operational application.

Figure 15. The ESA Earth-Observation Projects website (http://projects.esa-ao.org)

The new interferometric capabilities provided by the ASAR sensor, such as the various incidence angles or the improved revisit cycle, will benefit all previous applications. Also, topographic studies conducted by means of interferometry (Fig. 14), which are already benefiting from the combination of ascending and descending orbits and from data provided by ERS-2's Altimeter, will exploit such advanced instrument capabilities. Synergistic use of MERIS data will provide value-added information on land-cover or atmospheric artefacts.

ESA support to Project Leaders

All information submitted by the Project Leader to ESA is available to the Project Correspondent, an ESA expert appointed to follow closely a number of projects in a given discipline or geographical area. The Correspondent is the ESA focal point with whom not only to raise technical matters, specific to individual projects, but also to discuss broader issues related to progress in the research and development, science and application domains.

ESA is supporting quick publication/promotion of the interesting results from its AO-driven scientific projects. It has opened the EO Projects website (http://projects.esa-ao.org), where Project Leaders can publish their project's latest achievements as 'Hot News' (Fig. 15). Search facilities such as browsing by application, instrument, country, test site, Project Leader's name, institute, project title, objective or other keywords will allow all users to retrieve information about the on-going EO projects. The website also has a private area where all reports, materials or publications produced can be stored and submitted on-line to ESA by the Project Leader.

Thematic workshops and conferences

In the exploitation phase of the Envisat mission, the Agency together with its Project Correspondents, will organise a number of thematic workshops that will give the Project Leaders the opportunity to present the results of their current AO research project activities and to discuss the state-of-the art in their respective Earth-sciences disciplines. Position papers, progress reports on on-going projects, and demonstrations of running application prototypes will constitute the main form of communication in these workshops. One of the primary objectives is to foster the development of cross-disciplinary and cross-regional research activities and to encourage the development of innovative research ideas leading to new research projects or application developments.

Good examples of more recent ESA-organised (and co-organised) workshops that were well received by the research community are: Fringe (November 1999, Liege), the CEOS SAR subgroup (October 1999, Toulouse), the ATSR Workshop (June 1999, ESRIN), and ESAMs (January 1999, ESTEC). These workshops have been complemented by ESA Symposia (Fig. 16) like the ERS-Envisat Symposium held in October 2000 in Gothenburg (S), which attracted a large audience and was reported upon in ESA Bulletin No. 105.

Beyond the AOs: the new Earth-Observation Data Policy

The possibility of conducting scientific research using ESA-provided data continues beyond the Envisat AO. The new Data Policy, applicable for ERS and Envisat, allows proposals to be submitted at any time, beyond the fixed dates normally imposed by an Announcement of Opportunity. Having been approved by ESA's Earth-Observation Programme Board (PB-EO), it aims to maximise the beneficial use of EO data from both the ERS and Envisat satellites and to stimulate a balanced development of scientific, public-utility and commercial applications.

Under the new Data Policy, the conditions of data distribution for ESA EO data are directly related to the category of use. Two different categories have been defined:

Category-1 Use: Research and applications development use in support of the mission objectives, including research on long-term issues of Earth system science, research and development in preparation for future operational use, certification of receiving stations as part of the ESA functions, and ESA internal use.

Category 2 Use: All other users who do not fall into Category-1, including operational and commercial use.

Under the new Data Policy, some 48 Category-1 projects are already in progress, and 22 further projects are under evaluation. Further information can be found on the ESA EO Projects website at: http://projects.esa-ao.org.

Figure 16. The Proceedings of recent ESA thematic workshops and conferences, available on CD-ROM from ESA Publications Division

Conclusions

The Envisat mission provides Europe with a unique and unprecedented tool to improve our understanding of the Earth and its environment. The work of the scientists within the framework of the ESA AOs is the core process for answering the scientific questions and fostering the development of new applications in the field of Earth observation. The fact that the new Data Policy allows one to submit new proposals to ESA at any time will further increase flexibility for accessing Envisat data for scientific use. The Agency's coordinated support to the Project Leaders through the 'Correspondent' scheme should further sustain the development of science and focus the applications for EO data.

The Envisat Exploitation Policy

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Building on the ERS achievements
The ERS missions were originally designed to serve the science community and to demonstrate operational capabilities. Shortly after the launch of ERS-1, objectives for meeting operational requirements, in particular from the meteorological services, and for developing commercial distribution and application of the data were added to the mission goals. Accordingly, the ERS Data Policy addressed:
- scientific users
- commercial users, and
- meteorological users, as a particular case of operational use.

The Envisat mission, like its predecessors ERS-1 and ERS-2, is designed to respond equally to scientific, operational and market needs. The satellite's instrumentation, the ground segment and services and the overall exploitation policy, i.e. the high-level operations planning and the Data Policy, are aimed at satisfying all three areas of interest.

ERS scientific use
In support of the scientific users, ESA released a series of Announcements of Opportunity (AOs) that were initially aimed at general science and led to the development of new products and services and to application-demonstration projects. Data provision to the scientific users was complemented through agreements with receiving stations and research entities, which directly served the national science communities (Fig. 1).

Over the last 10 years, some 72 000 Synthetic-Aperture Radar (SAR) and the global Low Bit Rate (LBR) data products have been distributed by ESA to more than 3500 individual scientists working on more than 1200 projects. Several thousand scientific publications have appeared, not only in journals dedicated specifically to remote sensing, but also in magazines such as *Science* and *Nature*. These publications, as well as the large number of scientists attending the ERS-related ESA Symposia, have served as an impressive demonstration of the achievements of this policy vis-a-vis the scientists.

ERS commercial use
In 1991, ESA appointed a single consortium, consisting of Eurimage, Spot Image and Radarsat International, as its worldwide commercial ERS data distributor. National receiving stations were assigned the distribution rights within their territories for the data that they acquired.

With the ERS Data Policy, applicable from 1991 to 1999, ESA fixed the prices to be charged to end users, allocating a percentage of the revenue to the distributors. These prices depended on the processing level, the product type and the delivery medium, and ranged from 250 Euro for a medium-resolution SAR scene, to more than 2000 Euro for a terrain-corrected, geo-coded SAR product covering an area of 100 km x 100 km (Fig. 2).

In 1994, in order to foster better cooperation with the science community, ESA and the commercial distributors introduced an additional 'research' price scheme for the data, which was about 30 to 50 % of the commercial price. This scheme led to a steady increase in the commercial sales of ERS data, starting from less than 3% in 1992 and reaching some 15% today.

ERS operational Low-Bit-Rate services

Under the former ERS Data Policy, special conditions were granted to WMO-associated meteorological services. These organisations received the ERS Fast-Delivery Low-Bit-Rate (FD-LBR) products from the Wind Scatterometer, the Radar Altimeter and the SAR Wave Mode free of charge, on the understanding that these products were used only for forecasting purposes. This service was implemented by direct delivery of the ERS UWI, UWA and URA products into the Meteorological GTS Network. In recent years, this arrangement no longer provided sufficient transparency concerning the ultimate use of the data. Therefore, the fast-delivery products from the ATSR and GOME instruments are now being made available for downloading to all users, including the meteorological services, via password-protected servers.

The new exploitation policy for Envisat and ERS

Objectives and principles of the new Data Policy

The new Data Policy both for Envisat and ERS is aimed at:
- maximising the beneficial use of ERS and Envisat data
- ensuring accomplishment of the mission objectives defined and agreed by Member States in the programme proposal
- defining the rules for ESA and its partners to serve and support users, in both science and applications.

The definition of the new Policy was based on the experience gained through eight years of ERS exploitation, and was amended and adapted to the latest ideas for funding Earth-observation missions and their exploitation, and to the policies of other (non-ESA) Earth-observation missions.

Compared to the previous ERS Data Policy, major progress was made in the following areas:

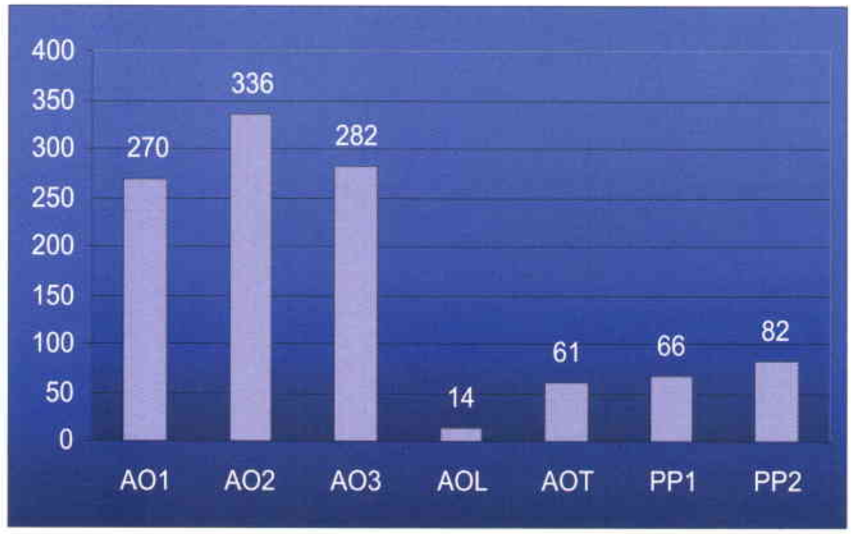


Figure 1. Projects accepted within the framework of ESA ERS Announcements of Opportunity and Pilot Project Schemes since 1991 (not including additional science-oriented projects organised via national activities/stations)

Table 1. Sample prices for SAR products (in Euros) under the original ERS Data Policy

Product description	Commercial price	Research price
Fast-delivery image	500	200
Annotated raw data	1000	200
Reduced-resolution scene	250	125
Single-look complex image	1200	500
SAR precision image	1200	300
SAR geo-coded image	1400	500
SAR terrain geo-coded image	2300	1000
Educational data products	90	90

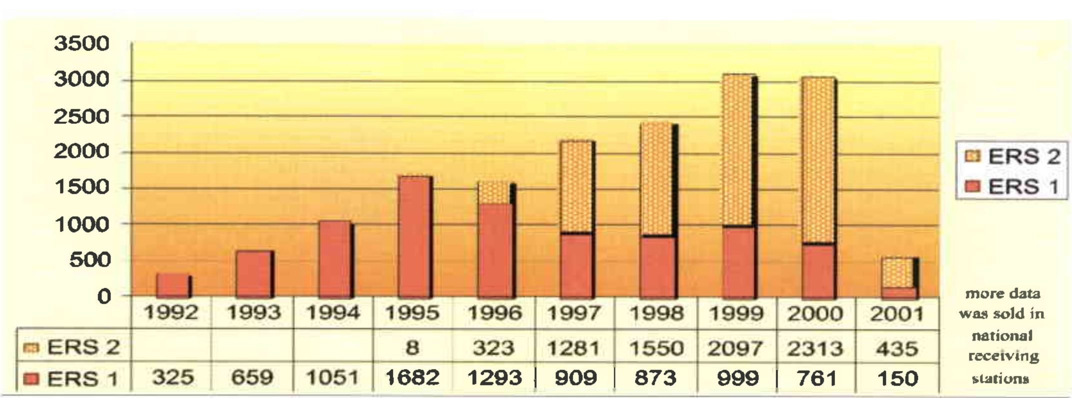


Figure 2. SAR scenes sold since the start of the ERS-1 and ERS-2 missions (commercial and research priced products)

Category-1 Use

'Research and applications development use in support of the mission objectives, including research on long-term issues of Earth system science, research and development in preparation for future operational use, certification of receiving stations as part of the ESA functions, and ESA internal use'

- Ensure continuity with the former AO system
- Rules for identification fixed in Annex C of Data Policy (e.g. Peer Reviews, AOs, Negotiated and approved Agreements with other Space Agencies or International Research Organisations
- Served by ESA
- Cost of reproduction; waivers to be approved by EO Programme Board

Category-2 Use

'All other uses which do not fall into Category-1 use, including operational and commercial use.'

- Served by appointed Distributing Entities (open market)
- User Price at discretion of Distributing Entities
- Distributing Entities may negotiate directly with NFS for Category-2 use

I. The new Data Policy is based upon the use made of the data, rather than on the user. This principle aims at providing equal data access conditions for similar applications and projects. Approved research projects will be granted the same rights and duties, whether they are handled by publicly funded research organisations/institutes or private companies. All services and all operational use of data, independent of whether the services are offered by public or private bodies, will be subject to the same conditions.

II. A clear definition of scientific use (Category-1) or any other use (Category-2), and the mechanism for identifying them, form part of the Data Policy. Any other use of the data, for example, in an international cooperation or as part of national projects of ESA Member States, has to be approved and serviced according to these two mechanisms. The user interface for Category-2 use has been fully delegated to distributing entities, while ESA retains full responsibility for Category-1 use.

III. The responsibility for market and service development is largely delegated to industry. The agreements between ESA and the so-called 'Distributing Entities' are contracts including formal and mutually agreed commitments for investment, market-development activities, delivery times, success-oriented discount schemes to increase sales, etc. In order to ensure competitive market conditions and to give users a choice, two consortia with overlapping world-wide distribution rights were selected. It is also foreseen to cater to so-called 'niche markets' through the direct appointment of specialised distributors. This direct-appointment procedure will primarily concern entities from Participating States, including national fixed and mobile stations, and will take into account one or more of the following elements:
- actual or planned investments supported by Participating States in facilities and activities related to the distribution system
- the need to complete the geographical coverage offered by already appointed Distributing Entities
- the need to complete the range of services offered by already appointed Distributing Entities.

IV. The pricing scheme for the data was also updated. For Category-2 use, commercial Distributing Entities were given full freedom to offer data and services according to market prices and their own business plans. For Category-1 use, a price just slightly above the cost of the data-delivery medium was introduced. For projects approved by ESA's Programme Board for Earth Observation, data are provided free of charge.

V. Distributing entities may negotiate directly with national or foreign receiving stations with the aim of:
- offering stations technical capabilities and services via a professional distributing entity to a world-wide market, beyond the one directly accessible to the station
- enlarging and complementing the portfolio of products and services available to Distributing Entities through ESA
- developing links via the stations to local markets.

The full implementation of the new Data Policy for Category-1 and Category-2 users is a stepped process: for ERS, past agreements and contracts have still had to be honoured, while new arrangements, in particular for Envisat, are following the new principles.

Scientific use (Category-1)

Announcements of Opportunity

Approximately 750 Envisat AO projects were accepted and approved as early as 1998. Some of them, in particular the Calibration/Validation projects, have already started and are receiving limited amounts of ERS data free of charge. This year, the leaders of these projects will have the opportunity to update their data requirements submitted in the original proposal. These revised requirements will be carefully evaluated and an appropriate data allocation – of ASAR and MERIS high-rate products in particular – will be granted. The exact allocations will be determined based upon the absolute needs to meet the objectives of the approved project, and upon an evaluation of the practical feasibility of generating and delivering the requested data. The Project Leaders will then be able to submit their actual data requests directly to the Order Desk via the Payload Data Segment (PDS).

Category-1 projects

With the implementation of the new Data Policy, the submission of new project proposals has become possible on an ad-hoc basis, and not only in response to the issue of an Announcement of Opportunity (Fig. 3). Some 25 such projects have already been reviewed and accepted over the last three months, and a further 16 are currently under review. These data are being provided at reproduction cost. The procedures for submission, evaluation and acceptance of Category-1 projects are described in a separate article (by Y-L. Desnos et al.) in this Bulletin, and on the dedicated web site: http://www.projects.esa-ao.org.

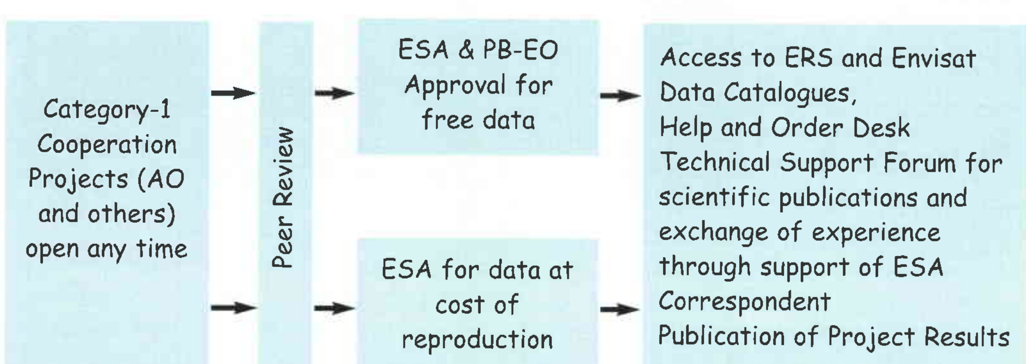
Terms and conditions for Category-1 use
The Project Leaders of all approved Category-1 projects, including the AO projects, will be asked to sign ESA's standard 'Terms and Conditions for the Utilisation of Data' before they can submit data requests. They are based on a similar contract used in the past for the ERS AO projects. The Project Leader will be asked to confirm that:
- the data are to be used exclusively within the framework of, and for the purposes described within, the accepted project proposal
- the data are not to be distributed to users outside the approved list of cooperating investigators
- regular progress reports and a final report will be provided
- the project results will be presented at ESA Workshops and Symposia
- the ESA copyrighting of the Envisat and ERS data will be respected.

Cost of data for Category-1 use
The data for Category-1 use are normally provided at the cost of reproduction. In exceptional cases, such as Announcements of Opportunity (AOs), for example, and following the approval of the ESA Programme Board for Earth Observation, the data may be provided free of charge.

The price range for Category-1 use of Envisat data will be similar to that for ERS data (e.g. 100 – 300 Euro per ASAR scene). Prices for LBR products will be mainly dictated by the supporting medium and can be free of charge for data downloads from servers. A final price list for Envisat Category-1 data use will be published after the satellite's launch later this year, in line with the product-validation campaign.

Cooperation with funding agencies and international research entities
ESA, through its Category-1 use scheme, offers data at favourable conditions or even free, and provides support to users in the form of tools, a help desk, a forum for exchanging and publishing results through symposia, web sites, journals and through its 'Correspondent' scheme. This scheme not only offers full transparency to ESA Member States and other users, but is also a tool for on-line monitoring of the projects' progress and results by national and other funding agencies. Such cooperations are being agreed upon with the Netherlands, the United Kingdom and the European Commission, and are open to other agencies. Throughout the approval process, the funding agencies' experts may participate in the review process. Some of these experts may themselves act as Correspondents for specific projects. A similar cooperation within a Category-1 framework is foreseen with large international research entities.

Category-2 use
Appointment of Distributing Entities
Contracts with the two Distributing Entity consortia were signed in September 2000 after a long process of consultation and negotiation. Consultations started in September 1999, when ESA organised a Workshop with 47 companies to discuss ideas for setting up contracts for the commercial distribution of ERS and Envisat data. This Workshop was attended not only by the traditional data distributors, but also by representatives from the European aerospace industry and many value-adding and service companies. The feedback gathered led first to the release of an open, competitive Invitation to Tender, and then



EMMA

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Envisat
The improved Envisat characteristics over ERS are of great value to EMMA, which will focus on product and service development for diverse applications. Agriculture and vegetation will benefit from the multi-polarisation capabilities of the ASAR in discriminating crop types and soil moisture; geology and exploration will exploit the same capabilities not only on a regional scale, but also on a continental scale with the wider swath modes, at a fraction of the cost. For offshore applications, Wide Swath imagery with VV polarisation will be able to cover larger areas; differential interferometry with a 35-day repeat cycle will be able to measure small terrain displacements due to plate movements, and other similar events, such as subsidences or landslides.

Business expectations and marketing plan
By focusing on developing the market potential that has not been fully exploited so far outside Europe, major growth is expected during 2001 and 2002. With Envisat being able to offer more operational solutions for user needs, growth should follow a constant and steady pattern also for key applications such as disaster management. Furthermore, the use of the Artemis data-relay satellite will increase access to global data and allow quicker delivery to users also, through faster electronic delivery services.

SARCOM

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Envisat
Spot Image and its partners in the SARCOM Consortium have been selected by ESA to distribute data world-wide from the ERS and Envisat. SARCOM has brought together some major players in the satellite-imagery market, all of whom distribute SPOT, ERS/Envisat and Radarsat data as complementary offers and a complete range of products and services.

Business expectations and marketing plan
SARCOM will offer an unrivalled service covering radar data reception, distribution and sophisticated products and services tailored to pollution monitoring, natural-hazard management, marine applications and mapping . SARCOM's marketing strategy is based on providing multi-sourced, complementary optical and radar data at low-, high- and very-high resolutions to boost development of the global market for satellite imagery and derived products and services.

to the setting-up of the two consortia, both comprising a number of companies offering a full range of services, from data acquisition to value-adding and information services. Negotiations with both consortia covered:
- business and marketing plans
- industrial commitments for investment and data purchase
- incentives and benefits for meeting and exceeding the business and sales targets set
- mutual commitments in terms of services, performance and quality
- possibilities for partnership projects with shared investment.

The current business plans are primarily based on sales of ERS SAR data, with ASAR and MERIS high-rate data forming the basis for business expectations in the Envisat time frame. LBR data, and in particular the data from the atmospheric instruments, are not included, since data from similar instruments on other missions are available under research conditions or at marginal cost. These data are therefore to be distributed by ESA under conditions similar to Category-1 for all uses, and will be made available for downloading from password-protected servers.

Despite the fact that both Distributing Entities offer world-wide services, for technical or political reasons certain markets may be accessible only to so-called 'niche distributors'. The Canada Center of Remote Sensing is one such case, currently being the only station operator offering ERS SAR Fast Delivery (FD) products over the area of interest to the Canadian Ice Service. Such 'niche distributor' contracts still allow a direct cooperation with either of the appointed world-wide Distributing Entities.

The expectations

The sum of commitments by the two Distributing Entities in terms of data sales for the first year already exceeds the sales of previous years. Following a stagnation in the commercial sales in 1999 and the first half of 2000, probably caused by the uncertain situation concerning prices during the on-going negotiations, the last quarter of 2000 (after signature of the contracts) showed a strong increase in sales, indicating that the commercial use of ERS data is still growing and exceeding expectations.

Based on a solid market analysis, the main application areas being targeted by the commercial Distribution Entities include: forestry, digital terrain modelling, ship routing, coastal management and fisheries, risk management (such as oil-spill monitoring, flood assessment, subsidence monitoring, etc.). Many of these SAR-, ASAR-, ATSR- and MERIS-based commercial applications are expected to develop at a greater rate in non-European countries. Fast world-wide availability and distribution of the data is therefore another key factor in the development of the commercial market.

Both Distributing Entities have begun negotiations with receiving stations for access to Envisat data and the introduction of these stations' services into the mission's portfolio. Both parties predict a yearly increase in commercial data sales of some 20% if Envisat operations start successfully as predicted (not later that 6 months after the launch), and if the reliability and data quality are similar to or exceed those of ERS. Key technologies for this evolution are, for example, the interferometric exploitation of the ASAR data.

Both Distributing Entities are actively promoting and marketing the Envisat data, including the development of tools and special value-adding services. These activities will be set up in partnership with ESA, and will then either be available to all users, or fully funded by one consortium only and then offered to just the customers of that consortium.

Commercial prices can be negotiated directly with the Distributing Entities and are expected to be competitive with those of other satellite missions.

Both Distributing Entities have a strong interest in maintaining links to the science community as a basis for the development of operational applications and commercial services. Thus, scientific users may, beyond the Category-1 scheme, request favourable data-access conditions by cooperating with a Distributing Entity.

Conclusion

During its initial implementation, the Envisat and ERS Data Policy is proving to be flexible enough to cope with all of the requirements from the research and commercial communities. Furthermore, it is also providing a framework for cooperation with national, European and international institutions. The further definition of Envisat product costs during the satellite's Commissioning Phase will complete the implementation of this exploitation policy. esa

Focus Earth

The Velingara Circular Structure – A meteorite impact crater?

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Planetary exploration has shown that virtually all planet surfaces are cratered from impacts. It is now clear that impacts have been a dominant geological process throughout the early Solar System, and also that the Earth has experienced the same bombardment as the other planetary bodies. In more recent geologic time, there is evidence that at least one mass-extinction event, notably that of the dinosaurs and many other species 65 million years ago, is linked to global effects caused by a major impact event.

Most of the terrestrial impact craters that have ever been formed, however, have been obliterated by other terrestrial geological processes, such as sedimentation and over-thrusting. However, relatively recent events and impacts can still be found in very old geologic formations that remain exposed. To date, approximately 150 impact craters have been identified on Earth. Almost all of them have been recognised since 1950, and several new structures are being found each year.

Observing our Moon, the morphology of impact craters changes with crater diameter. Only the smallest impact craters have a bowl-shaped form. As the crater diameter increases, slumping of the inner walls and rebounding of the depressed crater floor create progressively larger rim terracing and central peaks. At larger diameters, the single central peak is replaced by one or more peak rings, resulting in what are generally termed 'impact basins'.

On Earth, the basic types of impact structures are either simple structures, up to 4 km in diameter, with uplifted and overturned rim rocks, surrounding a bowl-shaped depression partially filled by breccias, or complex impact structures and basins, generally 4 km or more in diameter, with a distinct central uplift in the form of a peak and/or ring, an annular trough, and a slumped rim. The interiors of these structures are partially filled with breccias and rocks melted by the impact.

The study and understanding of impact craters has become a concern for the preparation of missions to the Moon and to other planets, notably Mars. Unlike most impact phenomena in the Solar System, such structures on Earth are easily accessible and can be imaged by many different Earth-observation satellites. In order to contribute to such a catalogue, observations have been collected from ESA's two ERS spacecraft. An example of the potential for observing and measuring the morphology of possible impact events using the Synthetic Aperture Radar (SAR) aboard ERS is given below.

The 48 km-diameter Velingara circular structure in Senegal (Fig. 1) was first discovered on Landsat and NOAA AVHRR images. Developed in mid-Eocene marine sediments, it has been buried by up to 90 m of post-Eocene non-fossiliferous continental sediments. Its central part constitutes the Anambe basin, which hosts the SODAGRI agricultural enterprise, and in which centripetal drainage concentrates in a swampy area of hydromorphic sandy-clayey soils. According to drilling and geophysical data, the central part of the structure is occupied by sub-cropping (3 - 4 m depth) Neoproterozoic or Palaeozoic basement rocks. These features point strongly towards a possible meteorite-impact-crater origin for the structure. Decisive evidence of shock metamorphism is now being sought, by analysing thin sections from surface and drilling-core rock samples.

The series of images presented here shows first a Landsat-5 Thematic-Mapper image in which the existence of a ring structure is suggested by the concentric arrangement of the different land covers (Fig. 2). In corresponding data from ERS's SAR sensor (Figs. 3a and b), the structure is even less pronounced. The

Figure 1. Location map of the study area

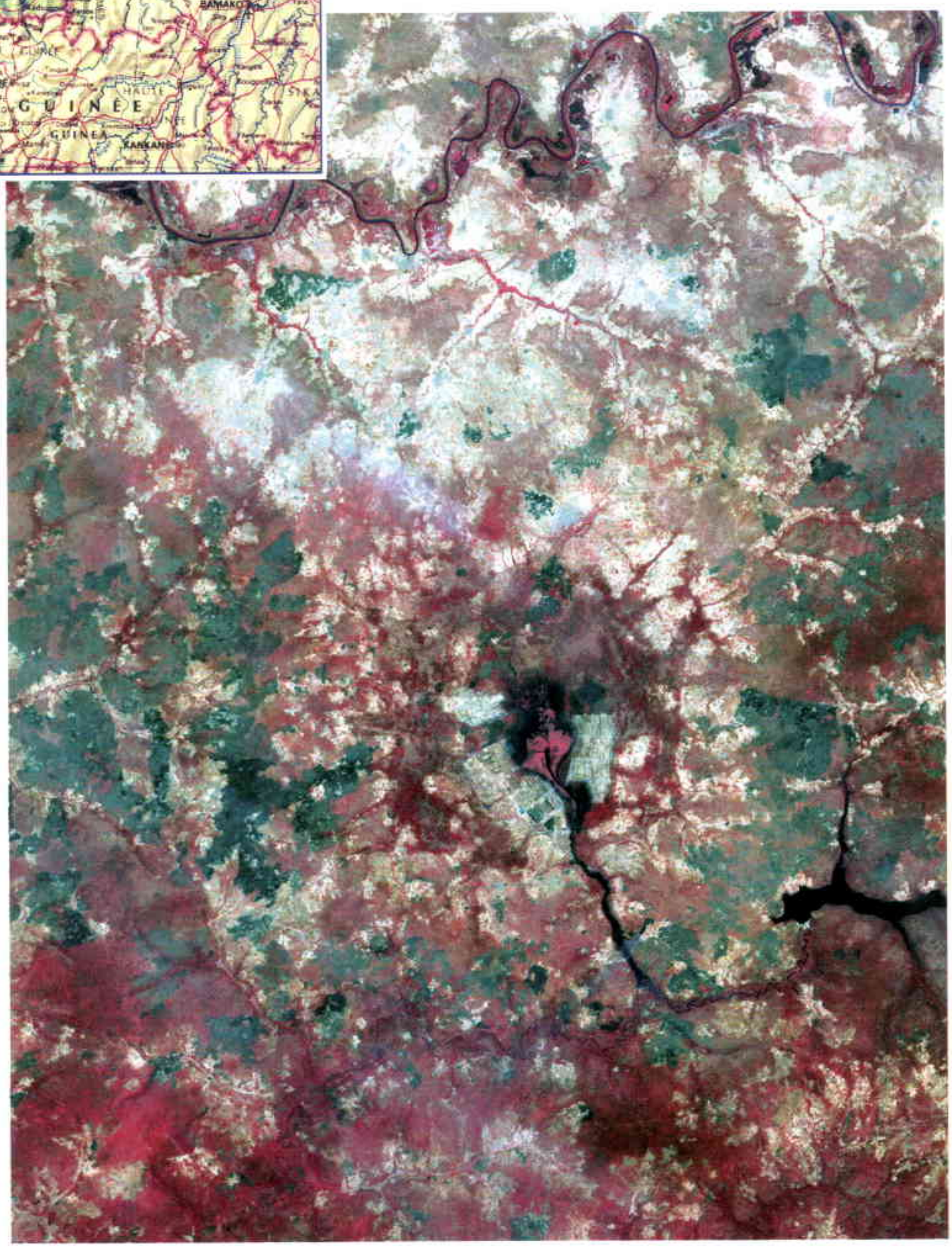


Figure 2. Landsat-5 Thematic-Mapper imagery (TM bands 4,3 and 2 in red, green and blue, respectively). The ring structure, first seen in such data, is highlight by the land-forms and drainage patterns:
- **White: bare soil; white spots are spaces around a house or village**
- **Dark greenish-blue: laterite of bare soil covered with dry grass**
- **Cyan/green: bare soil of agricultural fields**
- **Light red/magenta: green trees of savannah vegetation and gallery forest**
- **Dark red: dense shrub or forest**
- **Red-brownish: extensive shrub, in leaf.**

vegetated shallow lake is just visible in the centre, and the land cover is represented in different grey levels, with forested areas being brighter. Some of the towns and villages appear as bright points, including the town of Velingara.

Two radar images acquired by ERS-1 and ERS-2 during the tandem-configuration phase (with the two satellites acquiring data over the same ground area 1 day apart), were the basis for producing several SAR interferometric products, the first being a coherence image (Fig. 4). This image evaluates the degree of phase conservation, which is proportional to the temporal variation in the ground conditions between the two ERS acquisition dates. In this image, bright tones correspond to no change or high coherence. In general, they correspond to very low or scarce vegetation. This coherence image shows a similar pattern to Landsat, but with radial arrangements more pronounced, most likely due to the drainage system.

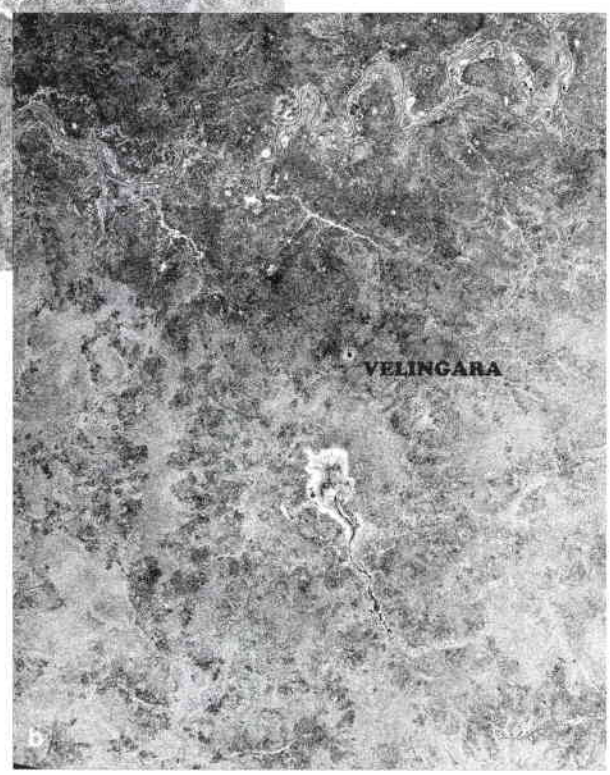


Figure 3. ERS SAR amplitude data over the area (69 km x 88 km), with the Gambia River visible to the north:
a. ERS-2 SAR on 24 December 1995, orbit 03541, frame 3342
b. ERS-1 SAR on 23 December 1995, orbit 23214, frame 3342

Figure 4. Coherence image (phase correlation between the two acquisitions) computed from an ERS tandem pair of SAR images, taken on 23 and 24 December 1995. Bright areas represent high coherence, which include scarce vegetation and settlements. Dense vegetation is less coherent and appears darker, while water always appears black (no coherence). Coherence images are also useful for DEM quality assessment and for change detection

Interferometric Synthetic Aperture Radar (InSAR) is a technique for extracting three-dimensional information of the Earth's surface by using the phase content of complex radar data. The technique involves the use of pairs of SAR images from the 35-day repeat-pass ERS-1 or ERS-2, or the 1-day interval ERS-1/ERS-2 tandem orbits. An InSAR product is the interferogram, which is obtained by computing the phase differences between the corresponding pixels in the two input images. Another product is the coherence image, which depicts the changes in ground conditions between the two acquisitions. Using these products and passing through the phase-unwrapping (phase-to-height conversion), a Digital Elevation Model (DEM) is generated

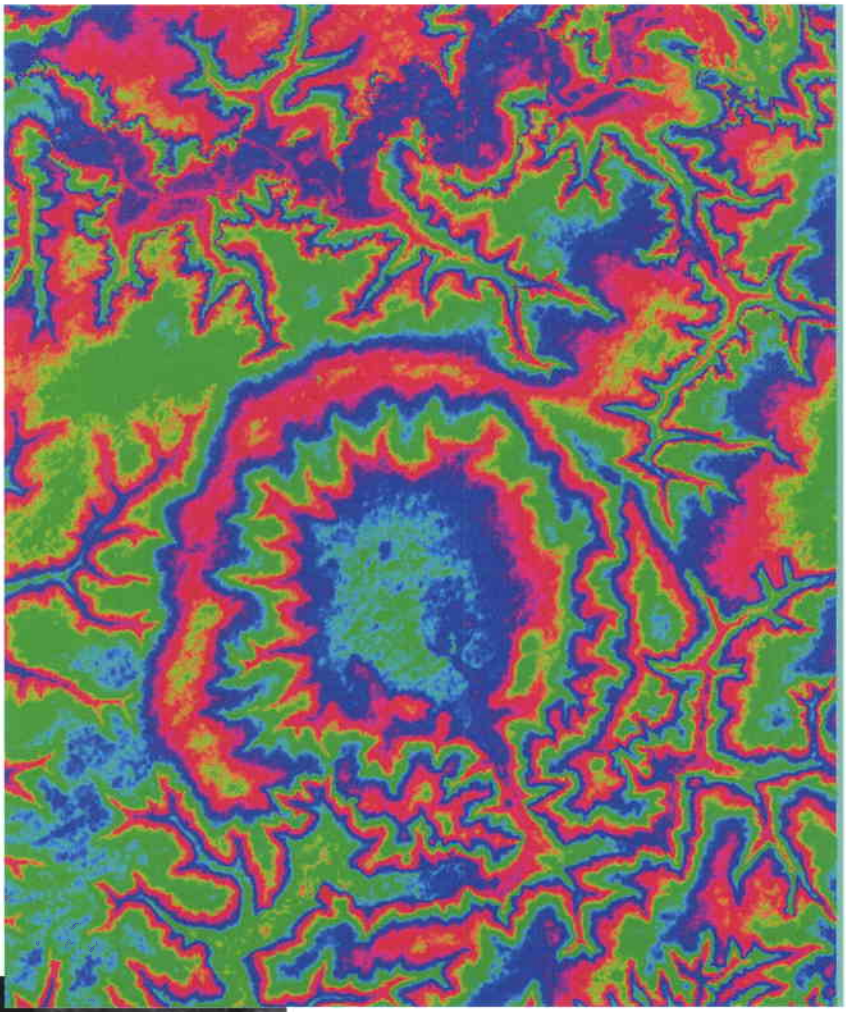
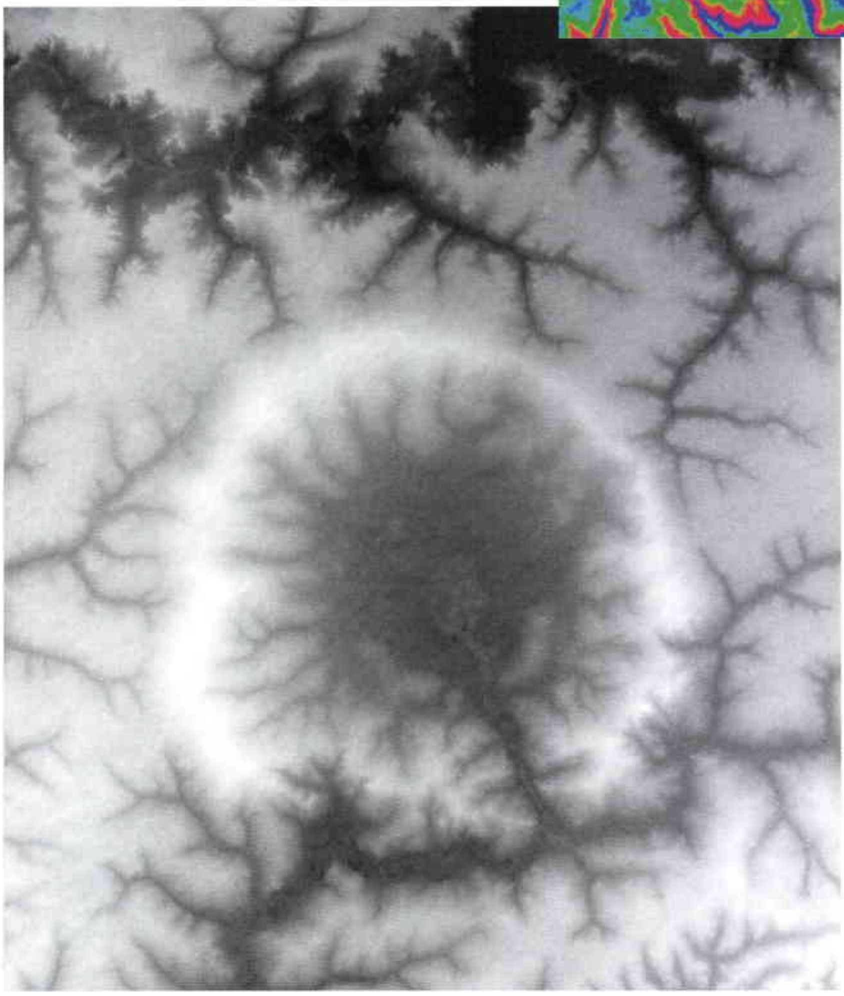


Figure 5. Interferogram derived from the 23/24 December 1995 ERS SAR tandem pair. The interferometric fringes, which represent phase differences between the two data sets, are colour-coded (from blue = 0 deg, to red = 360 deg). They resemble contour lines on a topographic map. Each fringe cycle represents a relative height change of 26 m. Due to the height differences, the morphology can be appraised: a ring structure is clearly visible



Height differences can be visualised by quantifying the phase difference (Fig. 5) between the dual-input SAR data. In this fringe image, the circular structure becomes clearly visible, and the radial drainage system towards the centre of the crater is also evident. Similar to contour lines on a traditional topographic map, each fringe cycle, from red to green, to blue and again to red, represents a relative height change of 26 m in either direction. This value is derived from the perpendicular distance between the two precisely known orbits, which was determined to be 346 m.

A further computational step is the unwrapping of the fringes, resulting in quantitative height information. The final step of computing a Digital Elevation Model (DEM) consists of transforming the pixel values in the unwrapped image from radians to metres. Figure 6 shows the resulting data set in a black and white display, representing low and high elevations, respectively. The ring structure is now clearly

Figure 6. A Digital Elevation Model (DEM) derived from the fringe image (interferogram) by phase unwrapping and phase-to-height conversion. Higher areas are bright, lower areas are dark

visible, but details in the landforms cannot be distinguished. The morphology of the ring structure can be optimally enhanced by artificially illuminating such a DEM. This is illustrated in Figure 7.

Finally, a combination of illuminated DEM and colour-coded height information can be produced (Fig. 8), permitting a full appreciation of both the morphology and the absolute height. On this final product, not only is the height information on the well-developed circular structure evident, but it becomes clear that there are also indications of further elements typical for large impact craters, namely the remains of one or two concentric 'peak rings' in the 'impact' basin.

In conclusion, it can be said that, considering:
- the small altitude variations in the zone of interest
- the fact that the ERS SAR pair used in this case was not the best in terms of baseline and coherence,

the InSAR methodology seems very promising for producing DEMs of remote areas, even in low topography. DEMs generated with SAR interferometry can find a broad spectrum of applications, ranging from the planning of mobile-telephone networks and roads or railways, to geo-tectonic analyses in which land forms, fault mapping and geomorphic features in general, have a high priority.

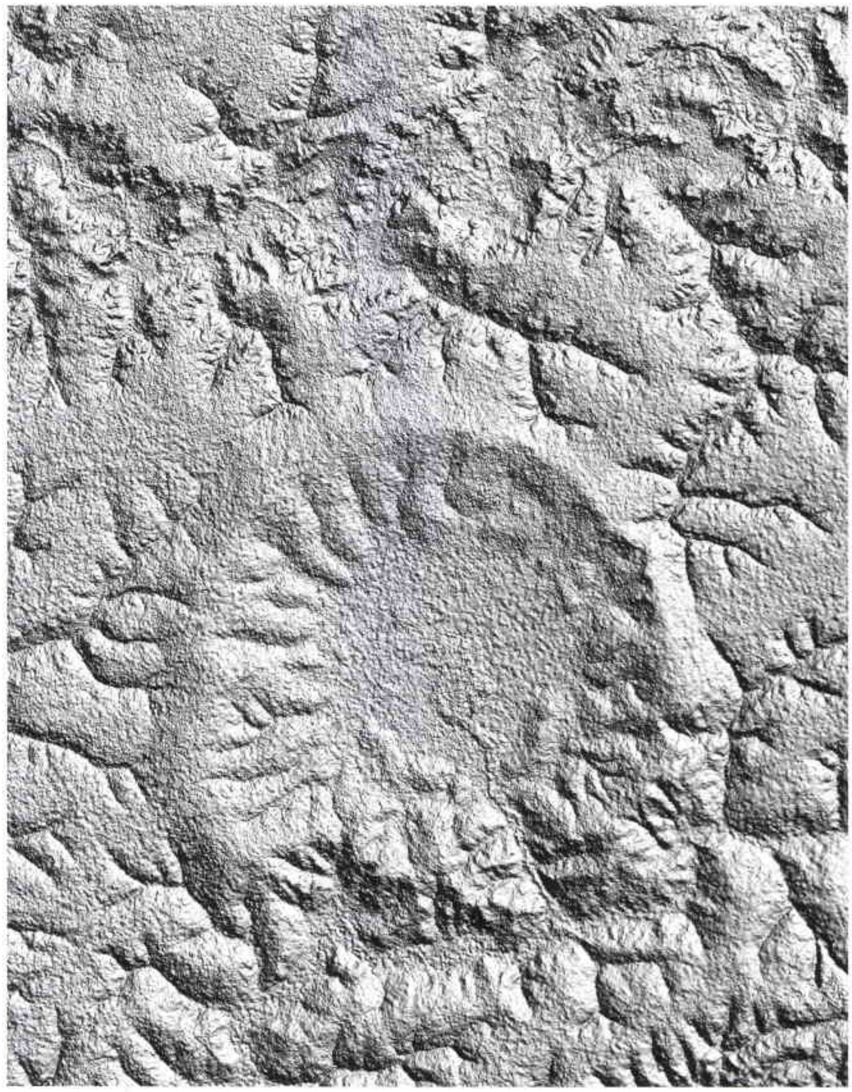


Figure 7. Hill-shaded relief based on the DEM as shown in Figure 6. The relief scale has been exaggerated to emphasise the morphology of the ring structure

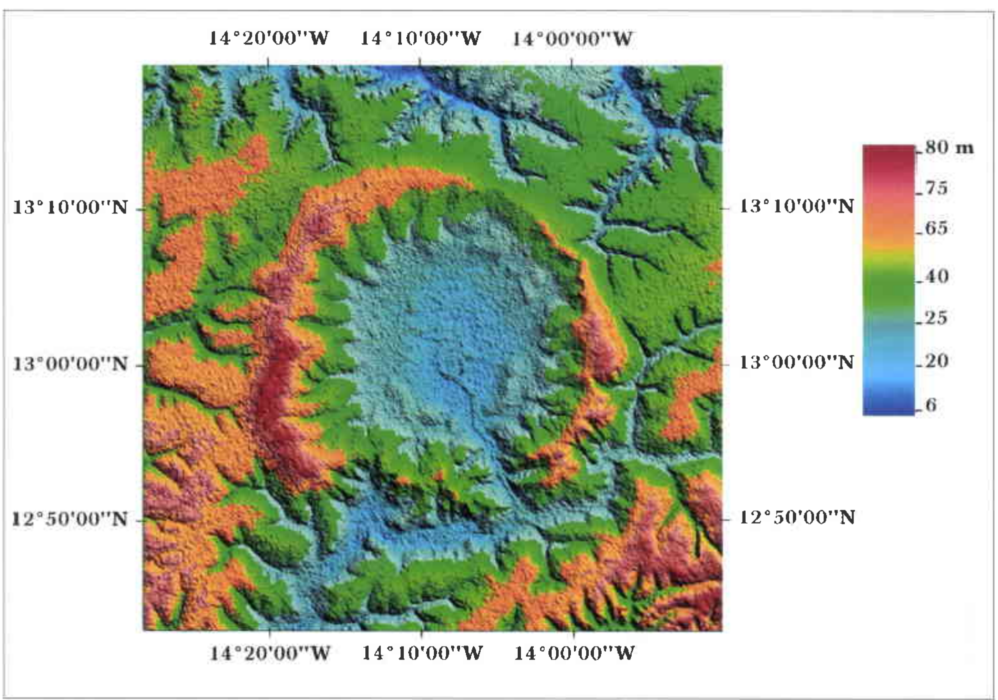


Figure 8. After geo-coding of the data by using the ERS orbital information (SLCI product header file), the final product is an image-map including the hill-shaded relief of the DEM and the colour-coded height information. The remains of a multiple ring pattern, a characteristic for large impact craters, are apparent (image size 69 km x 67 km)

Acknowledgement

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Wave Summit Course
Edited by: F. Takahashi, F. Kondo and Y. Takahashi
2000, 274 pp., hardcover
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The most notable results obtained by VLBI so far has been the global-scale measuring of the movements of the tectonic plates which cover the surface of the earth. Details of this achievement are discussed in the book, but the primary focus of the material covered here remains an investigation of how VLBI can conduct these measurements with such high level of precision.

Digital Broadcasting
Wave Summit Course
Edited by: T. Shiomi, M. Hatori
2001, 286 pp., hardcover
ISBN: 1 58603 099 X
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Broadcast television commenced in Japan in 1953, and nearly a half-century has passed since then. The presence of television continues to grow and TV broadcasts are the most familiar source of information for most people. This book compiles the fundamentals of digital broadcast which has rapidly developed since the advent of text caption broadcasting in 1985 as well as the most advanced technology including terrestrial broadcast, satellite broadcast and CATV (cable TV)

Global Environment Remote Sensing
Wave Summit Course
Edited by: K. Okamoto
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ISBN: 1 58603 101 5
Price: NLG170/EUR77,14/£49/DM152/US$70

Today we face various global environmental issues. Examples include the rise in atmosperic temperature due to the increase of atmosperic carbon dioxide, the depletion of the ozone layer and El Nino related climatic anomaties. Remote sensing technologies that use electromagnetic waves are quite useful in measuring physical parameters which describe global environments. This book covers de theory of electromagnetic remote sensing and the basic technologies used.

Mobile Communications
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Edited by: H. Sasaoka
2001, approx. 306 pp., hardcover
ISBN: 1 58603 100 7
Price: NLG160/EUR72,60/£46/DM143/US$65

Recent developments in mobile communication have been remarkable as typically seen by the increasing use of mobile and Internet phones. The traditional analog technology used in these communications is also being replaced by digital technology. The textbook covers an extensive range of subjects on land mobile communications from the basics to key technologies including digital transmission technology and code divirion multiple access.

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Edited by: T. Teshirogi, T. Yoney Ama
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This is an advanced textbook which extensively covers the study of millimeter-waves from the basics to the state-of-the-art millimeter-wave devices and application systems. Subjects are arranged and described in an easy-to-understand format.

Satellite Communications
Wave Summit Course
Edited by: T. Iida
2001, approx. 424 pp., hardcover
ISBN: 1 58603 085 X
Price: NLG170/EUR77,14/£49/DM152/US$70

Satellite communication technology is indispensable for land and maritime communications as well as broadcasting. This textbook explains the basic technologies required in understanding satellite communications. While focusing on the digital satellite communication method, detailed descriptions are also given on the low-orbit satellite communication system, as recent subject in the news.

Science of Space Environment
Wave Summit Course
Edited by: T. Ondo and K. Marubashi
2001, approx. 350 pp., hardcover
ISBN 1 58603 097 3
Price: NLG170/EUR77,14/£49/DM152/US$70

This book describes the basic physical images of the space environment extending from the sun to the earth as well as series of phenomena caused by its solar activities. Special emphasis is placed on how fluctuations in the space environment affect space itself and our social systems here on earth.

Space Communications

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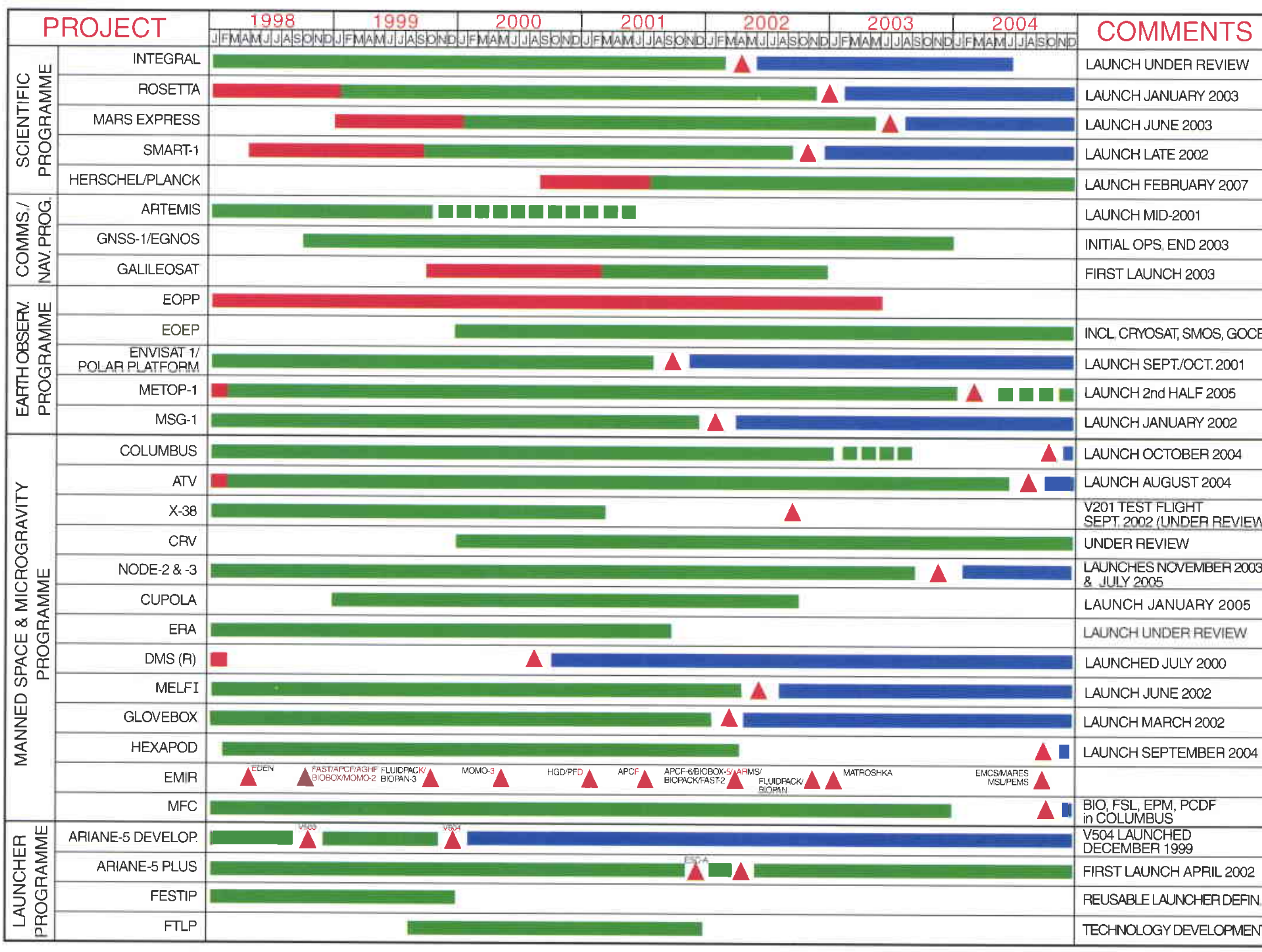


DEFINITION PHASE — MAIN DEVELOPMENT PHASE — ▲ LAUNCH/READY FOR LAUNCH

OPERATIONS — ADDITIONAL LIFE POSSIBLE — ▼ RETRIEVAL — STORAGE

Cluster

Following the completion of all commissioning activities at the beginning of January, nominal scheduled operations commenced. The successful completion of the Mission Commissioning Results Review (MCRR) on 1 February at ESA Headquarters in Paris allowed the start of the nominal Mission Operations Phase (MOP), with routine acquisition and tracking operations.

At the beginning of each ground contact, the contents of the onboard solid-state recorders have been dumped and correctly processed on the ground. Payloads have been correctly operated according to Joint Science Operations Centre (JSOC) inputs to the mission planning. All subsystems have been performing nominally.

A penumbral Moon eclipse at the end of January and several short eclipses in February were experienced by all four spacecraft, without problems and without restricting payload operations.

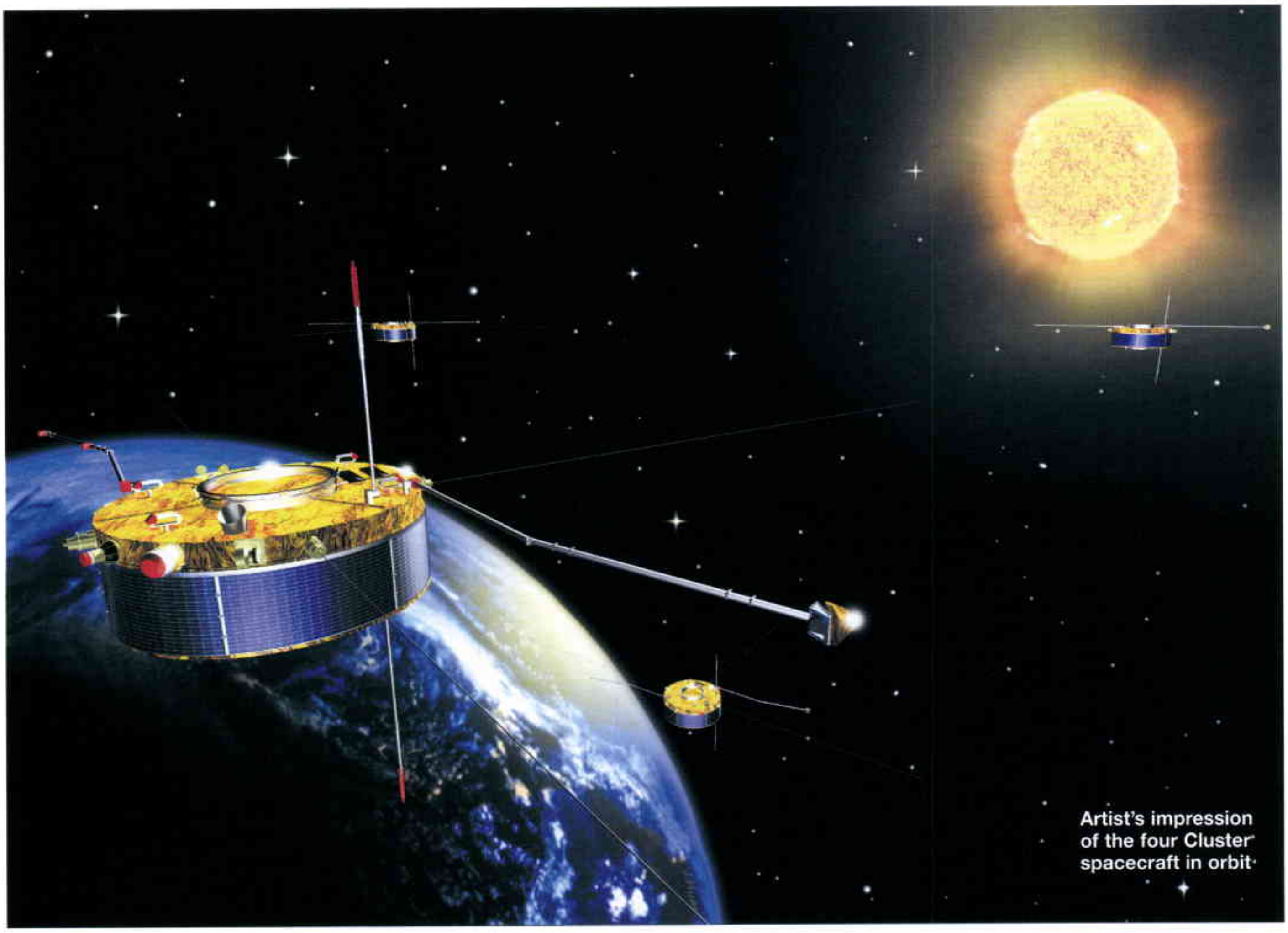
Contacts with the Chinese National Space Administration (CNSA) regarding possible European participation in the Chinese Double Star project have intensified. The cooperation would involve the provision of a certain number of flight spare units from some Cluster experiments to be flown on two Chinese spacecraft – one polar and one equatorial orbiting – to be launched by two Long March 2C vehicles in December 2002 and June 2003, respectively.

LISA and Smart-2

Following the approval by the Science Programme Committee (SPC) at its meeting last November of LISA as a Cornerstone mission in cooperation with NASA, of Smart-2 as a LISA and Darwin technology-demonstration precursor mission, and the later reconfirmation at the February meeting of Smart-2 as a fully European two-spacecraft mission, activities have received a new impulse.

LISA is a mission configured to detect gravitational waves from massive black-holes and binary stars in the frequency range 0.1 mHz – 0.1 Hz. To do this, three spacecraft fly in an isosceles triangle formation, of side $5x10^6$ km and with one spacecraft at each apex. Each spacecraft contains proof-masses that are kept in a drag-free environment, shielded from all forces except that due to gravity. The mutual positions of the proof-masses are measured continuously by means of a laser interferometer. The configuration thus forms a large Michelson-type interferometer in which the proof masses are effectively adjustable elements. Gravitational waves differentially disturb the proof-masses, so generating a measurable signal.

The technology-development activities required by Smart-2 and LISA in the fields of inertial sensors, metrology and drag-free propulsion have been started. A LISA Test Package Architect (LTPA) will be selected to coordinate the technology-development activities and the scientific community's inputs. Two industrial contractors will soon start parallel work on the Smart-2 mission-definition phase,



Artist's impression of the four Cluster spacecraft in orbit which will last until March 2002. The subsequent Phase-B is planned to start in November 2002.

The Smart-2 mission will fly the European LISA Test Package (LTP), aimed at validating the LISA drag-free technology, and the US one, if available, along with the Darwin Test Package (DTP), which will test formation flying and inter-satellite metrology at the micron level. The Smart-2 launch is currently scheduled for 2006, with the in-flight demonstration of the LLTP at the end of 2006. This will provide inputs to the LISA design phase (Phase-B), which will last until October 2007. The LISA launch is scheduled in the 2011 time frame.

Integral

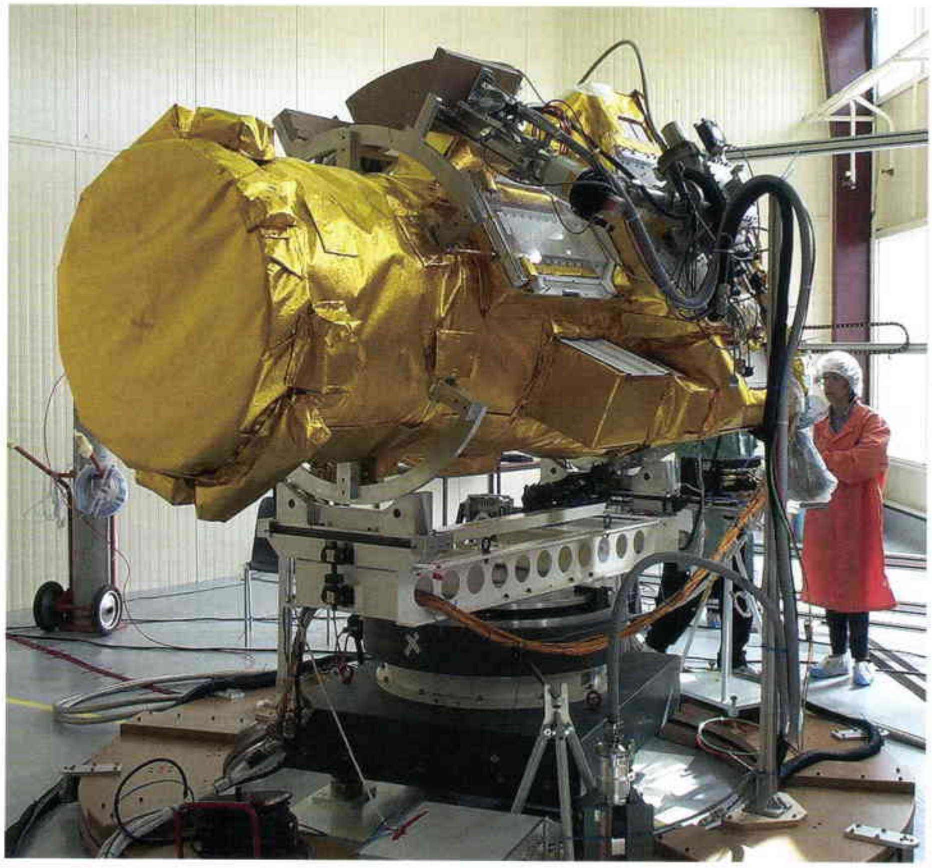
The Spectrometer (SPI) has successfully completed the flight-model tests and is on track for delivery in May to Alenia Spazio's facilities in Turin for integration into the spacecraft. The Optical Monitoring Camera (OMC) has been integrated on the spacecraft since last October.

Meanwhile it has become evident that the technology-development difficulties encountered by the Imager (IBIS) and X-ray Monitor (JEM-X) instrument teams cannot be solved in time to allow the planned launch in April 2002. The project is therefore currently rescheduling the remaining tasks to enable the inclusion of these instruments with minimum overall schedule and cost implications.

The ground-segment activities are progressing according to plan. System Validation Test (SVT) campaigns with the satellite have demonstrated a high degree of readiness.

The launcher Mission Critical Design Review (MCDR) has started and is progressing well. A concise data package has been submitted allowing a systematic review. The main objective of this review is to assess the adaptation of the Proton launch vehicle and the Baikonur launch facilities to the specific requirements of the Integral spacecraft launch.

The scientific community has confirmed its great interest in the project by submitting a record number of proposals for the use of guest-observer time on the observatory.



Integral Spectrometer (SPI) flight-model calibration in progress at the CEA facilities in Bruyères-le-Châtel

Rosetta

The first phase of Electrical Qualification Model (EQM) testing is being concluded in May. The integrated system tests have been performed on the subsystem and payload units. An EMC test has been completed with positive results in terms of the electromagnetic compatibility of the spacecraft. The EQM programme has suffered from various spacecraft and checkout-equipment problems, necessitating double shift working at the AIV site (Alenia in Turin) since the end of 2000. The second phase of EQM testing primarily involves software functions such as autonomy, failure detection and independent recovery and AOCS simulations. This second phase will last for the rest of the year.

Flight Model (FM) integration is continuing as planned, with the mechanical integration of the reaction-control system and thermal hardware onto the structure. The delivery of various equipment items is still critical and is being monitored closely; these include the power control unit, transponder and flight software. The Critical Design Review (CDR) process has started and will be completed in May.

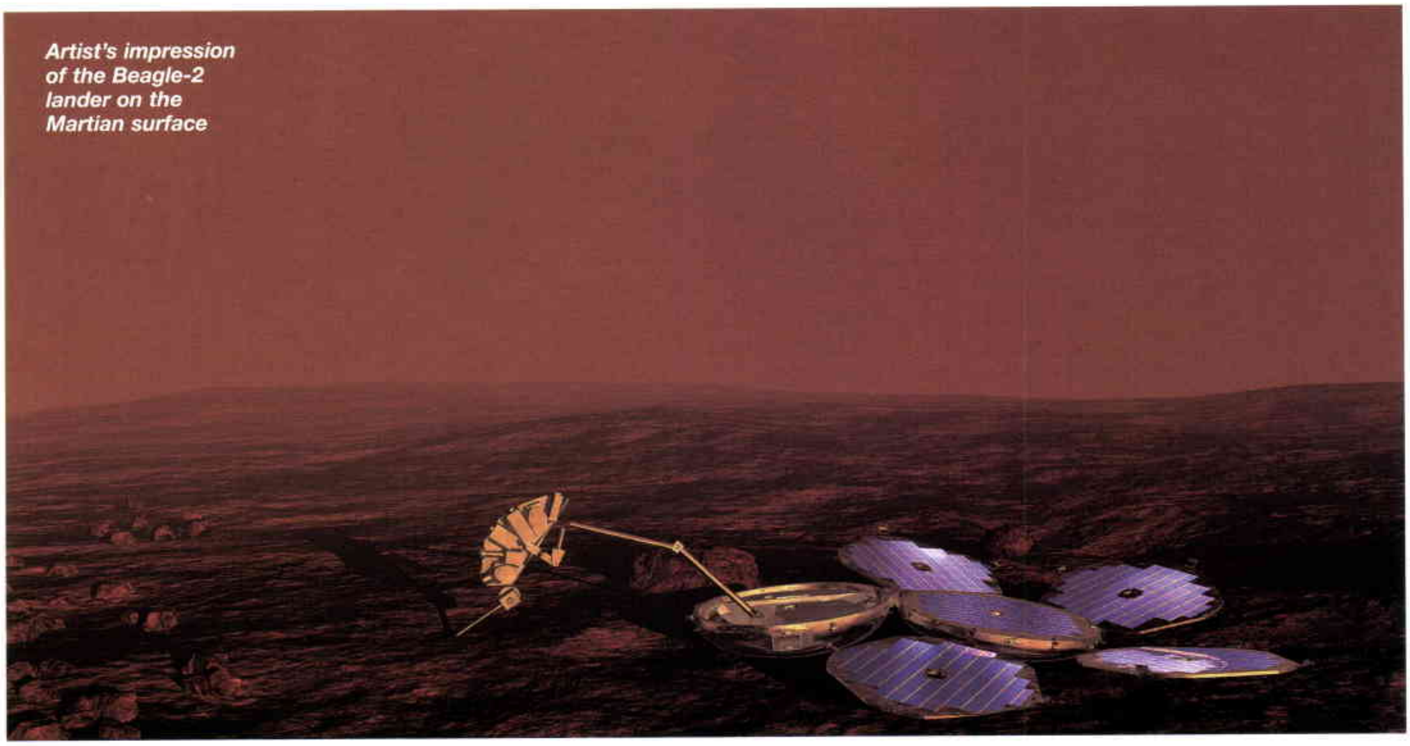
The experiment flight models are now in the final stages of testing and calibration at the various institutes, in preparation for delivery. The schedule is still critical for some payloads, particularly the main scientific camera, 'Osiris'.

The Lander flight model is completing its integration at the Max-Planck Institute in Lindau (D), with many items still on a critical path. The Lander Final Design Review was successfully completed in February.

The site infrastructure for the new 35 m antenna in New Norcia (W. Australia) is nearing completion, with commissioning of the overall antenna system expected by mid-2002.

Mars Express

The delivery of the spacecraft flight structure was the main event in early 2001. After q7ualification testing of the structure at Contraves in Zurich (CH), it was shipped to Astrium Ltd. in the UK, where integration of all flight-propulsion-system elements commenced in late March. The spacecraft will be moved



Artist's impression of the Beagle-2 lander on the Martian surface

several times during the year between the various specialised test and integration facilities in Europe.

The rolling review process for Beagle-2 continued with reviews of its instruments, the robotic arm and the mechanism on the spacecraft that ejects Beagle-2 and spins up it up at the same time. The Critical Design Review of the Orbiter instruments was nearly complete by the end of March. The preliminary conclusion is that production of the flight-model instruments can now be initiated by the various scientific teams.

The electrical testing of all spacecraft subsystems continues at Astrium SAS in Toulouse. By the end of March, nearly all engineering models of the instruments had been successfully integrated and tested.

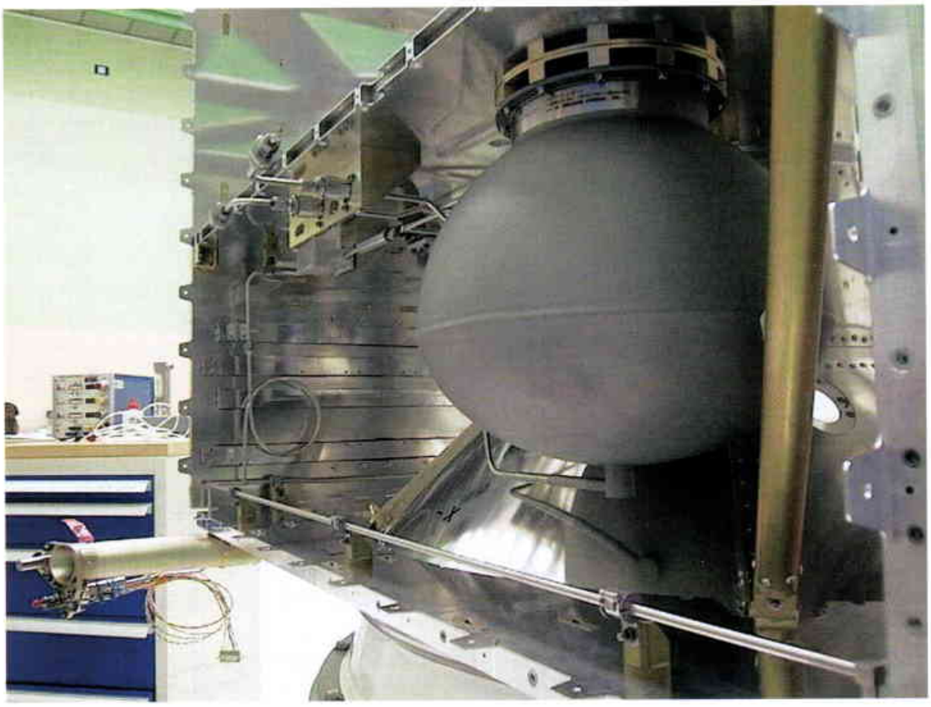
As regards the launcher, several meetings took place to optimise the performances of Soyuz and its Fregat fourth stage for Mars Express. The related activities are progressing quite well in the sense that the original launch ten-day launch window can probably be doubled in length.

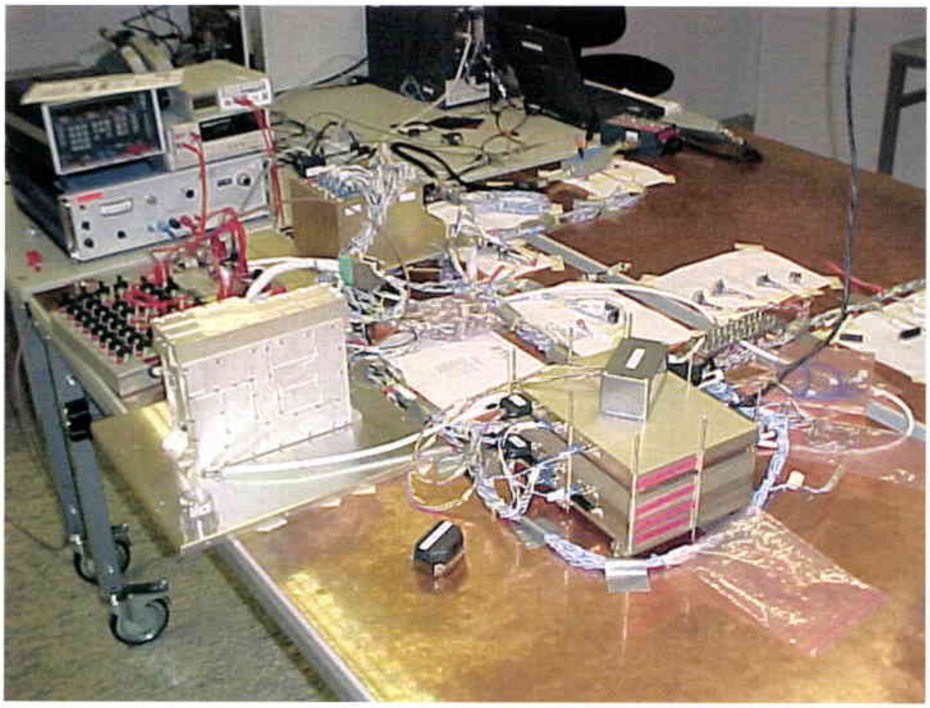
On the operational side, a major effort was initiated with NASA/JPL to identify all required interfaces for the inter-operability of landers in the 2003 to 2005 time frame. This capability is highly desirable as there will be at least two orbiters (Mars Express and NASA's 2001 Odyssey) and three landers (Beagle-2 and the two NASA 2003 landers). Cross-support between the two Agencies to maximise the scientific return will be of great benefit for the scientific community.

Smart-1

The Prime Contractor, the Swedish Space Corporation (SSC), is currently performing system electrical testing on the Bench Test Model at its Solna (S) premises. The first phase has been completed, with the testing of the 'core' avionics units: the System Unit (data-handling, telemetry and telecommand and pyro-control unit), the Power Control and Distribution Unit (solid-state power controller part) and the S-band Transponder. In parallel, four of the six instruments' electrical models have been successfully validated in another similar test set-up.

The Smart-1 structural model being integrated at the Saab Ericsson Space plant in Linköping (S). In the foreground are the hydrazine tanks and other components of the reaction-control system





The three Smart-1 main avionics unit electrical models – the S-band Transponder, the Power Control and Distribution Unit, and the System Unit (left to right in the centre of the photograph) – being tested in the Bench Test Model set-up at the Swedish Space Corporation's premises in Solna

The structural model (STM) is being assembled at Saab Ericsson Space's premises in Linköping (S). The primary structure manufactured by APCO has already been integrated with the reaction-control system. Other equipment qualification units or mass and inertia dummies will be integrated in the next month to arrive at a fully integrated Smart-1 STM ready to be shipped to ESTEC in Noordwijk (NL) at the end of May.

The spacecraft Critical Design Review will start at the end of June.

The six payload-instrument STMs have also been shipped to Linköping and will be integrated during April-May. The structural test on the integrated spacecraft at ESTEC will allow representative structural loads at the experiment unit interfaces to be derived, and verify their qualification.

The ground segment has undergone a design review, which concluded with a meeting of the Review Board in March. Procurement of the mission-control software, based on the SCOS-2000 kernel, has started.

Herschel/Planck

Evaluation of the Tender proposals for the Herschel/Planck spacecraft's development was completed in February and a recommendation sent to ESA's Industrial Policy Committee (IPC) for approval, which was given on 14 March. The contract, the largest so far for a space-science project undertaken by ESA, will be awarded to a European industrial consortium led by Alcatel Space Industries of France as Prime Contractor, with Astrium GmbH of Germany and Alenia Spazio of Italy as main contractors.

Alcatel will also be responsible for the Planck Payload Module's development and Planck spacecraft assembly and testing. Astrium GmbH will be entrusted with the development of the Herschel Payload Module (cryostat) and Herschel spacecraft assembly and testing, drawing on their extensive experience with cryostat technology for the ISO spacecraft. Alenia Spazio will provide the fully integrated Service Modules for both the Herschel and Planck spacecraft.

The kick-off meeting with Alcatel was held in mid-April, which shortly thereafter released to Astrium and Alenia their respective authorisations to commence work.

In March, NASA informed ESA that it will no longer be able to supply the Herschel telescope, due to budgetary restrictions. However, it did reaffirm its intention to remain active in supporting the Herschel/Planck scientific instruments and to provide the agreed hardware.

For the two Planck instruments – the Low-Frequency Instrument (LFI) and the High-Frequency Instrument (HFI) – the second round of formal Instrument Design Reviews with the ESA project were held in February. Significant progress has been made in the design of these instruments, but there will be a further review to finalise a number of system issues. Both instruments will enter their detailed design and development phases later this year. The same formal review has been conducted for PACS, one of the three Herschel instruments. The status of its system and subsystem design is satisfactory and that instrument is also approaching its detailed design and development phase. The reviews for the other two Herschel instruments, SPIRE and HIFI, will be held at the end of April.

The development of a common facility to allow vibration testing of the Herschel instrument focal-plane units at cryogenic temperatures has made a major step. An open competitive tender was released early in the year and the proposals from European facilities and industry are now due for evaluation by ESA.

The Invitation to Tender (ITT) for the Planck telescope reflectors, provided to the project via a Memorandum of Understanding with the Danish Space Research Institute (DSRI), was released early in the year in open competition. Proposals are expected by mid-May.

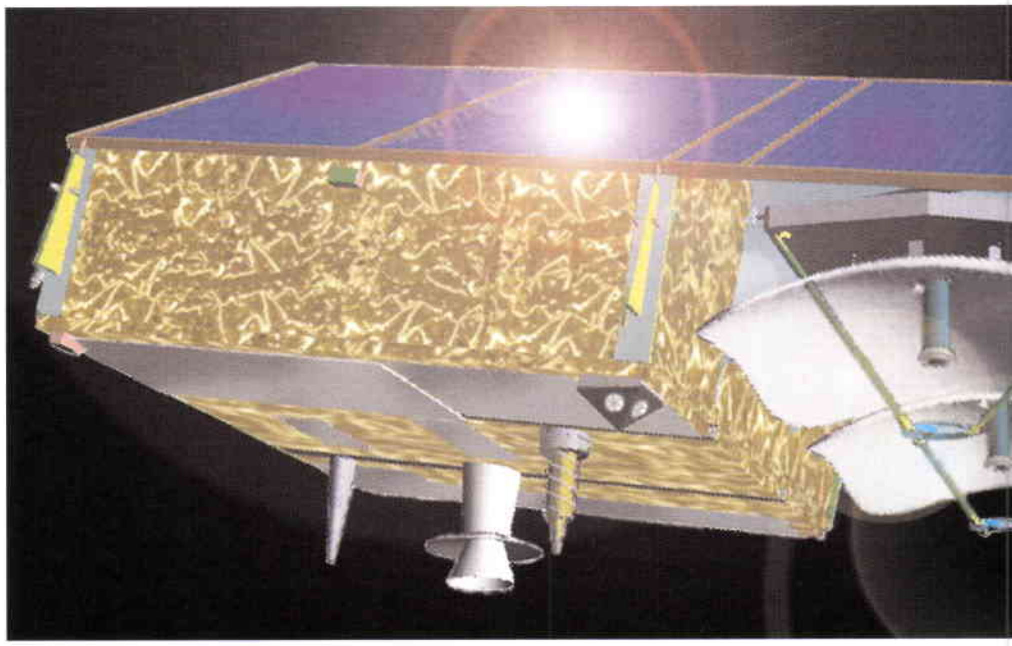
Artemis

In December last year, the ESA Council approved the budget for the procurement of a commercial launcher for Artemis and selected Ariane-5 as the launch vehicle. This move became necessary following an announcement by NASDA, the original launch-service provider for Artemis, that the first operational flight of their new H2A launcher would be delayed by at least 1.5 years. ESA and Arianespace subsequently agreed that Artemis should be readied as a 'stand-by passenger' for Ariane flight 510, scheduled for the beginning of June 2001.

In the first months of the year, numerous meetings where held to define the new launcher/satellite interfaces and to organise the launch campaign in Kourou (Fr. Guiana). In parallel, the Prime Contractor Alenia prepared the satellite – which had been stored in the ESTEC clean room since completion of the test programme about one year earlier – for transport to Kourou. Artemis left ESTEC by road on 16 March, heading for the French port of Le Havre, from where an Arianespace boat, the 'Toucane', carried the satellite and its support equipment to French Guiana. Some support equipment for the launch of Envisat later in the year formed part of the same shipment.

After Artemis' arrival in Kourou and its transportation to the launch centre, the launch campaign started immediately. All planned activities progressed smoothly and by mid-April the point had been reached where there can be no further activity without knowing the definitive launch date. The launch campaign will be resumed about five weeks prior to the actual launch date. In the meantime, the ESA and Alenia teams will return to Europe.

The potential launch dates have recently been shifted by Arianespace, with flight 510 now scheduled for 10 July (for which Artemis is still a stand-by passenger) and flight 512 (the nominal Artemis launch) for early September.



Earth Observation Envelope Programme (EOEP)

The CryoSat space-segment design phase (Phase-B) was completed in February with a System Design Review (SDR), which concluded that the expected performances could be met by the current design proposed by industry. Some consolidation work on specific system aspects will take place prior to starting the main development phase (Phase-C/D) in mid-2001.

The Earth Sciences Advisory Committee (ESAC) has conducted an independent review of the CryoSat project and has made a very positive recommendation for full mission implementation.

The Addendum to the GOCE Phase-B/C/D/E1 Contract Proposal was approved by ESA's Industrial Policy Committee (IPC) in January. The first progress meeting, held at Alenia Spazio in Turin in February, showed good progress in the Phase-B activities. The consolidation of the satellite baseline design and related interfaces is planned to be completed by the end of May. In accordance with the progress achieved on these consolidation activities, about 30 Invitation to Tender (ITT) packages for the various satellite elements will be issued in the April to June time frame.

Considerable effort was devoted to the preparation of proposals for the overall Earth Watch initiative and for the specific Ocean Earth Watch programme. A number of proposals for possible Earth Watch programmes are being evaluated.

The Adjudication Committee agreed the procurement proposal for the pre-development of the L-band SAR. It will be submitted to the IPC in May.

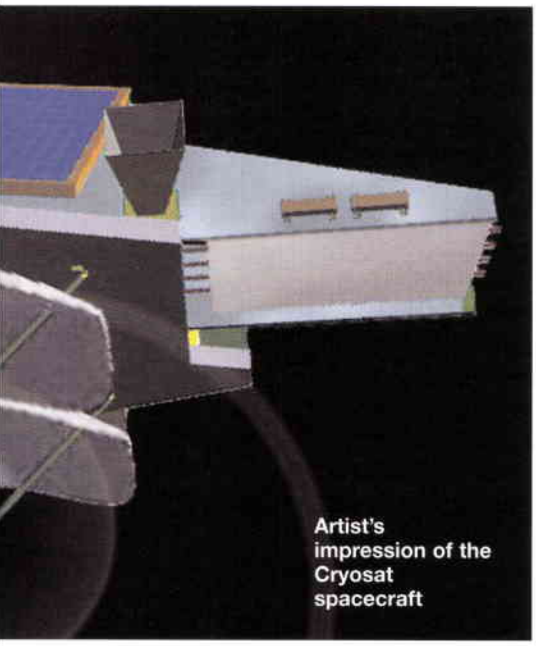
The two parallel design studies for the spaceborne ALADIN instrument, led by Alcatel Space Industries and Astrium SAS, are due to be completed in April. Both teams have generated designs and concepts for the pre-development model. The ITT package for the second phase of the pre-development programme (hardware manufacture) is being prepared. One of the two contractors will be competitively selected for the second phase (manufacture and test of a pre-development model of the instrument). This contractor will also become the instrument sub-contractor for the mission's Phase-B. The ITT package for the instrument's PRODEX-funded main development phase (Phase-C/D) is in preparation.

In the Market Development area, all 16 of the first batch of short-term contracts have been initiated. Four proposals for longer-term contracts have been selected and will be started in the next quarter. An ESA - Industry Briefing entitled 'New Opportunities Earth Observation Applications Development in 2001' took place at ESRIN on 2 March. This event attracted more than 60 European and Canadian companies, with a total of around 100 attendees, again demonstrating the strong industrial interest in this activity.

Earth Observation Preparatory Programme (EOPP)

Step 2 of the implementation mechanism for the second cycle of Earth Explorer Core Missions (mission assessment) has started and the scientific and technical activities are proceeding as planned. Science Preparatory Groups are in place, and all met during the first quarter. The industrial pre-Phase-A studies on the five missions under consideration (ACE, EarthCARE, SPECTRA, WALES and WATS) have been kicked-off.

Preparations for the Third Earth Explorer Consultation Meeting (Granada, October - November 2001) have been consolidated.



Artist's impression of the Cryosat spacecraft

The Joint Euro-Japanese Science Preparatory Groups and Engineering Teams met in March and satisfactory results were achieved in working towards a suitable EarthCARE mission concept. Some candidate missions still show considerable complexity and will require substantial effort to bring them within the programmatic constraints.

The scientific and technical activities on the SMOS mission continued, culminating with the Preliminary Concept Review held at the end of March. The challenge was to match the instrument resource requirements, derived from the science needs, with the capabilities of the Proteus platform. The ongoing work is focused on achieving convergence of the science, payload and platform design and satisfactory results are expected soon. The appropriate science and support studies have been initiated.

The Call for Ideas for the second cycle of Earth Explorer Opportunity Missions is ready for release, after approval by the Earth Science Advisory Committee (ESAC) in March. Consultation meetings were held with Eumetsat, and a seminar on future low-Earth-orbit systems was held on 17 January. The Earth Watch long-term plan has been aligned with Eumetsat's needs for the post-MSG/post-EPS period.

Meteosat Second Generation (MSG)

The delay in the launch of MSG-1 from October 2000 to January 2002 announced by Eumetsat resulted in the storage of the engineering model and first flight model (FM-1) in mid-January. This approach was confirmed by the Pre-Storage Review Board that met, as planned, in March. Work in Industry is now concentrated on MSG-2 and MSG-3, whilst awaiting a 'de-store request' from Eumetsat in order to prepare MSG-1 for launch.

The need to add a shock-test programme in order to qualify MSG-2, MSG-3 and follow-on models for Ariane-5 launches is still under investigation, but looks increasingly likely.

MetOp

The arrival of the Payload Module (PLM) engineering model in the ESTEC environmental test facilities at the end of March represented a significant step in the MetOp development programme. This model will be submitted to thermal-balance and thermal-vacuum testing in the Large Space Simulator (LSS) starting in May, to be followed by electromagnetic and radio-frequency compatibility tests lasting until September.

The PLM engineering-model activities accompany the ongoing satellite structural-model campaign at ESTEC. The structural-model satellite completed its acoustic testing in March. Its testing campaign is continuing with vibration and shock tests, and will cover the environmental test levels of both the Ariane-5 and Soyuz launchers. Completion of the structural-model test campaign is planned in May, after which the satellite structure will be released for refurbishment and re-use as the flight structure for the Metop-3 satellite.

Before being transported to ESTEC the Payload Module engineering model had been submitted to final integration tests at Astrium GmbH in Friedrichshafen (D), following the delivery of the GOME-2 instrument in early March. Astrium GmbH has also completed mechanical/electrical integration of the PLM proto-flight avionics, with functional testing now imminent.

Instrument integration on the PLM proto-flight model will proceed at a reduced pace subject to agreements on implementation of the MetOp restructuring programme, aimed at aligning the industrial activities with the delays in the delivery of Eumetsat-provided third-party instruments. The restructuring programme is intended to achieve a cost-optimised integration sequence for the three MetOp satellites and to deliver the first satellite flight model early-2005, in line with the revised Eumetsat EPS Ground Segment development planning.

The consequences of the EPS delay for the overall MetOp programme have yet to be settled in the framework of the ESA/Eumetsat Co-operation Agreement.

MSG-1 being prepared for storage, with MSG-2 being integrated in the background

Negotiations on the first phase of the MetOp industrial impacts involved in accommodating the change to the Soyuz-ST launcher are nearing completion, for presentation to the Eumetsat Council in June.

Finally, the 2001 cycle of MetOp Critical Design Reviews (CDR) commenced in March with the PLM and ASCAT CDRs, and will continue until October and the anticipated completion of the Satellite System CDR with Astrium SAS.

Envisat

System

The system activities have been focused on:

- supporting the Flight Acceptance Review (FAR)
- supporting the Ground Segment Readiness Review (GSRR)
- preparing the satellite in-orbit switch-on and data-acquisition phases
- ensuring acceptance of the Payload Module Computer (PMC) software
- preparing the Integrated Satellite Tests (ISTs) and System Validation Tests (SVT- 3)
- supporting, together with Industry, the simulation campaign at ESOC.

Satellite and payload

The last major test of the European test campaign, the satellite Radio Frequency Compatibility (RFC) was started in early January and completed before mid-February. For this test, the satellite was installed in a specially-built RF protective enclosure and was nominally operated with radar (ASAR antenna deployed) radiating, telemetry/telecommand links operating, and radiometer/spectrometer instruments in their operational receiving modes. This test was completely successful and in particular permitted the ASAR to be operated in its nominal flight configuration: ESOC was given the opportunity to control and operate the ASAR in this configuration to validate the corresponding flight-operations procedures.

The PMC software was formally accepted. This flight version was then used to conduct the last Integrated Satellite Tests (ISTs) and the last satellite tests under ESOC control before launch, the System Verification Tests (SVT-3), which were successfully completed by mid-April. The Flight Acceptance Review, which started on 19 February, was satisfactorily concluded, with the Board sitting on 3 April. The completion of the formal satellite verifications will be reported to the Board before Envisat is shipped to Kourou (Fr. Guiana). A fit-check with the Ariane-5 adaptor will be performed before demating of the satellite. The Service Module and the Payload Equipment Bay will then be installed in their own containers for air transport, by an Antonov-124 aircraft, to Kourou. Two Boeing-747 freighters will carry the Electrical Ground-Support Equipment (EGSE) and spare flight units. These shipments are planned for mid-May 2001. Upon arrival in Kourou, the Envisat satellite and its supporting equipment will be deployed in the newly available S5 integration facilities at the Centre Spatial Guyanais (CSG).

Unfortunately, ESA was informed by Arianespace in early March that Envisat could not be launched during the summer as originally requested, due the prevailing easterly winds expected then. For a northerly launch of the sort required for Envisat's injection into a Sun-synchronous orbit, these onshore winds at stratospheric altitude create a potential hazard over populated areas of French Guiana in the event of a major launcher failure. The Envisat launch slot has therefore been rescheduled for the period 24 September to 24 October.

After analysis, it was concluded that the most efficient approach was to start the Envisat launch campaign in mid-May as originally planned and to put the campaign on hold from 20 July until 28 August, at which time it will resume with satellite fuelling, integration of the satellite on the launcher, and the actual launch.

Ground segment and plans

The Ground Segment Readiness Review (GSRR), started on 12 February, was completed with the following conclusion: while for the Flight Operations Segment (FOS) the situation was judged satisfactory, for the Payload Data Segment (PDS) the late delivery of the PDS V3 has also delayed the remaining validation activities and operation training. Taking this situation into account, as well as the early timing of the GSRR with respect to the final launch date, a delta GSRR review will be held at the end of July.

For the FOS, flight-operations-procedure production is well advanced and the operations simulations started in early February. As far as the PDS is concerned, acceptance of the various centres and stations is still in progress, with the PDS V3 overall acceptance planned for mid-April. The Ground Segment Overall Validation (GSOV) has concentrated on validation of the mission-planning interfaces between the FOS and PDS. The PDS V3 generic elements have been delivered to the Processing and Archiving Centres (PACs), and the PAC overall integration with the PDS is planned to start in May. Operator training and operations rehearsals will start soon at the PDS facilities.

The calibration and validation activity preparations are progressing according to plan with regular meetings of the participants. The in-situ data-acquisition campaigns are being re-planned to cope with the launch delay. A new data-circulation-rehearsal campaign, using the PDS User Service Facility, will be organised shortly. A workshop to present and review atmospheric instrument calibration and product validation is planned for mid-May. A second workshop to review the meteorological products together with the meteo user community is planned for early July.

The Envisat communications campaign has been defined and Delegations have been invited to interact with the Agency for the organisation of national events. A well-attended Press Day was held at ESTEC on 1 February.

International Space Station

ISS Overall Assembly Sequence

Two successful assembly flights to the ISS took place during the first quarter of 2001. The first, Assembly Flight 5A (STS-98), was launched from Kennedy Space Centre (KSC) on 7 February. During this mission, the US Laboratory 'Destiny' was assembled with 'Unity' and Space Station attitude control was transferred from 'Zvezda' to 'Destiny'. The Pressurised Mating Adapter 2 was moved from 'Unity' to 'Destiny' to become the primary Shuttle docking port. The second flight, Assembly Flight 5A.1 (STS-102), was launched from KSC on 8 March. The primary tasks for this mission were to provide outfitting equipment for 'Destiny', stored in the first MPLM ('Leonardo'), including the first science racks and the Human Research Facility, and to launch the second resident crew and return the first crew.

Columbus Laboratory
The system Critical Design Review (CDR) and the independent NASA Safety Review II have been conducted successfully. The Final ESA/NASA Joint Board, which met on 18 January, concluded that the objectives of the CDR had been achieved. The PICA final integration has started. The pre-qualification tests on the electrical test model have continued, with fixes to various problems being applied prior to the start of qualification testing, planned for the beginning of May.

Columbus Launch Barter
Nodes-2 and -3
The Node-2 System Design Review 2 (SDR2), equivalent to a Critical Design Review, has been completed successfully, pending closure of the assigned actions. The Node-2 delivery to KSC is planned for September 2002, consistent with a November 2003 launch date. Structural qualification testing has been successfully completed (pressure, leakage and inertia loads). The Node-2 flight-unit proof pressure and leakage test campaign has started, and will be followed later this year by the modal survey test.

Crew Refrigerator / Freezer (RFR)
The Preliminary Design Review is scheduled to start in mid-June and the Accommodation Model is currently under construction.

Cupola
Pressure testing on the Cupola Structural Test Article (STA) has been completed without problems. Manufacturing of the flight-unit dome and ring has started. Design changes to the shutters, driven by the need for enhanced meteoroid/debris protection, are being negotiated with NASA.

Automated Transfer Vehicle (ATV)
Following achievement of the consolidation of the technical concept of the ATV at the PDR Board in December 2000, a recovery plan for the management and programmatics of the project has been agreed with industry. The management structure has been improved by a combination of reallocation of system tasks to the Prime Contractor, reinforcement of the Prime's team through the collocation of Astrium engineers, and collocation of the ESA Project Team at the Prime Contractor's site at Les Mureaux (F).

The Prime-Contractor, project-management and system-engineering tasks have been put under a cost-reimbursement regime, with a cost-sharing scheme in the event of an overrun. A corresponding contractual agreement protocol has been signed by ESA and industry and a contract Rider will be generated and signed after approval by the relevant ESA committees. The overall schedule is being consolidated taking into account the underlying assumptions.

The Structural and Thermal Model is progressing and the Cargo Carrier will be ready in July.

X-38/CRV and Applied Re-entry Technology (ART)
The second V131R drop test has been postponed in order to further evaluate the anomalous behaviour, observed during the first flight in November 2000, of the vehicle control system. Extra wind-tunnel tests in Europe have begun in support of the resolution of this anomaly.

Industry has been given technical consent for shipment of the three Fault-Tolerant Computers (FTCs), and the Acceptance Review of the CMC Leading Edge units has been successfully completed. Assembly and testing of the Landing Gear System (LGS) continues, and design activities for the International Berthing/Docking Mechanism (IBDM) have been initiated.

The CRV Phase-1 industrial proposal was found to be incompatible with the ESA Request for Quotation (RFQ) and therefore, following a debriefing by the Executive, industry has submitted a complete revision, which is now being evaluated.

Ground-segment development and operations preparation
The System Requirement Reviews for the Control Centres for Columbus and ATV have been successfully completed, and their main development phase (Phase-C/D) will be initiated later this year.

Utilisation

Preparation
The Space Station User Panel (SSUP) met for the first time with its new composition and Chairman in March. The new composition reflects, more than previously, both industrial and commercial representation, and also has European Science Foundation (ESF) participation. European Commission participation is anticipated. The SSUP made a specific recommendation encouraging full European co-ordination of programmes, both ESA and National. The Panel also examined the flight sequence for the ESA external payloads and recommended that flight priorities should only be assigned two years prior to the first scheduled flight and should be based on best science, utilisation priority and development status.

Hardware development
Following signature of the European Drawer Rack Phase-C/D contract last December, the lower level contracts are now being finalised.

The accommodation of the European external payloads on the Columbus External Payload Facilities (EPF) has been agreed with NASA. Under this agreement, ESA will free the three positions on the Express Pallet at the S3 site and retains the exclusive rights to use the Columbus EPF location for approximately 4.5 years. Furthermore, ESA retains the assigned utilisation flights with the Express Pallet, which is the baseline transport system.

The start of Phase-C/D for SOLAR/EXPORT and EuTEF is on hold pending assessment of the impact of the relocation to the Columbus EPF.

Astronaut activities
In January, C. André-Deshays started training at Star City for the Soyuz 'Taxi Flight' Andromède. The crew- and medical-support for the Andromède flight will be provided by the European Astronaut Centre (EAC).

A 'Delta' Basic Training Course at EAC, designed to complement and update the knowledge of ISS Systems for experienced ESA astronauts (C. André-Deshays, P. Duque, R. Ewald and T. Reiter), has been successfully concluded. This means they now meet the certification requirements of ISS Basic Training.

The first ISS Advanced Training will start on 2 April at Johnson Space Centre (JSC). Four ESA astronauts will participate (P. Duque, L. Eyharts, T. Reiter, R. Vittori) together with three from NASDA, one Russian and one from NASA. The ESA part of the Advanced Training will be conducted at EAC in mid-2002.

A third ESA Flight Surgeon has been certified as an ISS Flight Surgeon by the Multilateral Space Medicine Board (MSMB). The development of Columbus Systems Training started in February and the first hardware deliveries for the Columbus Trainers are expected in September 2001. The Astronaut Fitness Programme is continuing and has been extended to include astronauts based at ESTEC and JSC, in particular to provide fitness support to U. Guidoni in preparation for the STS-100 mission in April 2001.

Early deliveries

Data-Management System for the Russian Service Module (DMS-R)

The installation of all components of the Data Management system on board the 'Zvezda' module has been completed. After the arrival and docking of the US Lab Destiny to the 'ISS', a major planned software reconfiguration took place on the Russian side, such that both 'Zvezda' and 'Destiny' are now performing guidance, navigation and control of the entire ISS. It is planned to retain this cooperative control mode throughout the operational life of the Station.

European Robotic Arm (ERA)

The ERA qualification programme at system level is proceeding, but the conclusion of these activities with the Qualification/Acceptance Review has been shifted into early 2002. On the Russian side, no funding has been made available so far to allow the Science Power Platform (SPP) development to continue. As the SPP will accommodate ERA during launch, this event will have to be shifted further into the future. A delay of several years compared to the official SPP launch date of October 2002 is very likely, and will have to be accommodated in the ERA project planning.

Laboratory Support Equipment (LSE)

Extensive testing of the –80 degC Freezer (MELFI) engineering unit is in progress, together with the integration of the first flight unit. The Flight Acceptance Review (FAR) in Europe is scheduled for November, and MELFI will be launched on flight ULF-1 in mid-2002.

Testing of the Microgravity Science Glovebox (MSG) engineering unit is proceeding, and flight-unit integration is in progress. The FAR in Europe is scheduled for August, and launch will be on flight UF-2 in early-2002.

The Hexapod engineering unit is complete, the qualification model is in preparation, and the FAR in Europe is scheduled for November.

ISS Exploitation Programme

In line with the modified ATV development programme, the earlier planned procurement of the first ATV production unit has been put on hold and only advanced batch procurements of EEE parts and selected equipment have been authorised so far.

A draft Request for Quotation (RFQ) for the Exploitation Programme Operations Contract has been provided to industry in order to allow them to start preparing the proposal, which needs to be received and negotiated in time to prepare for the ESA Council Meeting at Ministerial Level in November.

Selected pathfinder projects for commercialisation have been further defined and the first project has entered its development phase. On the international side, diverging views on commercial utilisation among the ISS Partner agencies are still a major stumbling block to arriving at an agreed approach. Such policy agreements are essential for the business community to commit to firm plans.

Microgravity

EMIR programmes

Activities have continued to support near-term flight opportunities. Final agreement was reached with Rosaviakosmos on the pricing of the Foton-M1 mission that is due to take place in October 2002. NASA has announced that the STS-107 Spacehab mission, with six ESA life- and physical-sciences facilities, is delayed until 2002. Preparations continued for the Maxus-4 sounding-rocket flight on 29 April, the Maser-9 sounding-rocket flight in November, and the 30th parabolic aircraft flight campaign on 30 May.

Microgravity Facilities for Columbus (MFC)

Testing of the Biolab engineering model was completed in April, and manufacture of the flight model will start in May.

Some delays have occurred in the Materials Science Laboratory (MSL) and Fluid Science Laboratory (FSL) subsystem manufacturing activities, and the Critical Design Reviews will now be completed by end-April. The system-engineering model integration will be completed by April/May.

Phase-A/B for the Materials Science Laboratory using Electro-Magnetic Levitator (MSL-EML) technology has started. Implementation of the Microgravity Vibration Isolation System (MVIS) for the FSL, provided by the Canadian Space Agency, has also been initiated.

JOINT ESA - NASA SPACE-FLIGHT SAFETY CONFERENCE

SAFETY THROUGH PARTNERSHIP

esa NASA

The Main Topics of the Conference are :

- System Safety & Risk Management
- Payload Safety & Certification

with respect to:

- Design & Development
- Verification & Validation
- Operation of Space Systems

Objectives of the Conference:

- To provide an international forum
- To attract and maintain attention to safety
- To foster co-operation between NASA, ESA and other partners on the safety of space-flight projects
- To assess current practices and lessons learnt for space-flight safety

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- F. Cantelli (ASI)
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How to achieve the goal of: "flying to & returning safely from space" !

Web Site Address:
http://www.estec.esa.nl/conferences/01a04/

Conference Date:
6 - 8 November 2001

Conference Venue:
ESA/ESTEC Conference Centre,
Keplerlaan 1, 2200 AG Noordwijk,
The Netherlands

In Brief

New Director of Technical and Operational Support Arrives

Pieter Gaele Winters, who is Dutch, took up duty as the new ESA Director of Technical and Operational Support, based at ESTEC, on 1 June. His previous post was also in the space business, as President and CEO of Fokker Space BV, having had a career in the public sector in the Netherlands. He has always been active in the fields of industrial policy and technology and has been directly associated with the space sector since the early nineties. Mr Winters was also Chairman of ESA's Council from 1993 to 1996.

Umberto Guidoni: First European Astronaut on the ISS

The Earth has him back: ESA-astronaut Umberto Guidoni, from Italy, was the first European astronaut to fly to the International Space Station (ISS). Guidoni and his six colleagues from the USA, Canada and Russia spent 11 days on the ISS to deliver and return the European-developed Multi-purpose Pressurised Logistics Module "Raffaelo" (MPLM) and to attach the Station's new 17-metre Canadian robotic arm.

After a few computer problems in the US Destiny module, things went very smoothly and a satisfied Guidoni landed on Earth aboard the Space Shuttle "Endeavour" at the Edwards Air Force Base in California. *"Now the Station can at last begin to be used for its intended research purposes,"* noted Guidoni. A full article by Umberto Guidoni on his ISS activities and experiences will appear in the next issue of the ESA Bulletin.

More ESA Astronauts to Fly to the ISS: First Assignment for Roberto Vittori

European astronauts will fly at least one mission per year to the International Space Station (ISS) on Russian Soyuz launchers in the period 2001 to 2006. ESA's Director General Antonio Rodotà and the Director General of the Russian Aviation and Space Agency (Rosaviakosmos) Yuri Koptev recently signed an Agreement on cooperation between the two agencies.

ESA astronauts will perform the duties of flight engineer on "taxi flights" and "increment flights". "Taxi flights" are short-duration flights (7-8 days) to the International Space Station for the purpose of exchanging the Soyuz escape spacecraft. "Increment flights" are crew exchange flights which may require the astronauts to stay on board the Station for up to 3-4 months.

The Framework Agreement sets the general principles, terms and conditions of the ESA-Rosaviakosmos cooperation while the type of flight, the experimental programme content and the cost of each specific flight will be negotiated on a case-by-case basis. The total package price will include the cost for the training, planning and preparation of the missions, the onboard stay and the uploading and downloading of flight equipment needed for the specific experimental programme. The number of flight opportunities is currently not specified, but it will be in the order of one mission per year.

This agreement represents an important step in the development of operational expertise for the European Astronaut Corps before the intensive utilisation of the International Space Station for scientific research, Earth observation, technology development, material science and human physiology experiments, with the launch of ESA's Columbus laboratory in 2004. *"The agreement supports the Russian effort in the space arena with the involvement of European professional astronauts, and it shows a further sign of the increasingly strong cooperation between ESA and Rosaviakosmos,"* said ESA's Director General Antonio Rodotà.

The Italian Space Agency ASI has already taken the first option for a flight by an ESA astronaut. Roberto Vittori, an Italian national and a member of the ESA's Astronaut Corps since 1998, will receive his first assignment as flight engineer on the first available Soyuz taxi flight after October 2001. esa

Anniversaries and Farewells

This spring was a big season for space news. Biggest of all was of course the re-entry of the Russian space station Mir – everything went smoothly as the veteran station burned up when it re-entered the atmosphere on 23 March. Stargazers in the South Pacific witnessed impressive fireworks of burning parts – some even called it *"the most beautiful brake track in the world."*

The Mir re-entry marks the end of one era and the beginning of another with the occupation of the International Space Station (ISS). Exceeding its expected lifetime by ten years, Mir hosted 105 cosmonauts and astronauts from more than ten countries and a wide range of scientific experiments in its confined space.

Another event that attracted lots of attention (and many space enthusiasts to anniversary parties all over the world) was the 40th anniversary of Yuri Gagarin's trip around the Earth. The first man in space said during his trip, which lasted only 108 minutes, *"I can see the clouds! I can see everything! It's beautiful!"* After his safe landing back on Earth he commented: *"Circling the Earth in the orbital spaceship I marvelled at the beauty of our planet. People of the world! Let us safeguard and enhance this beauty – not destroy it"* esa

Foton-M1 Contract Signature

ESA signed a contract on 11 April with Russia's Rosaviakosmos space agency and Central Specialised Design Bureau (TsSKB) to fly a 355 kg payload from ESA, CNES and DLR on Russia's Foton-M1 recoverable spacecraft.

Foton-M1 is an improved version of the Foton/Bion-class satellites that ESA has used since 1987 for experiments. TsSKB builds the spacecraft and their Soyuz launchers. Nine missions have flown so far with ESA payloads, the most recent being Foton-12 in September 1999 (ESA Bulletin No. 101, February 2000). Foton-M1, scheduled for launch in October 2002, will carry ESA's FluidPac/TeleSupport and Biopan multi-user payloads in orbit for 16 days, complemented by experiments from young researchers in ESA's 'Outreach' programme. ESA has the contractual leadership of this scientific mission, allowing the Agency's investigators to share the CNES and DLR facilities aboard Foton (Ibis and Agat, respectively). ESA's planned 18 experiments cover fluid physics, biology, radiation dosimetry, exobiology, material science and meteoritics. esa

Mr Jörg Feustel-Büechl (seated, left), ESA Director of Manned Spaceflight and Microgravity, and Mr Viktor Kozlov (seated, right), Head of the Department for Unmanned Spaceflight at Rosaviakosmos, signing the Foton-M1 contract at ESA Headquarters on 11 April. Looking on are Mrs Jeanne Slagmolen, ESA Contracts Officer, and Mr Werner Riesselmann, Head of the Microgravity Payload Division at ESTEC.

Artemis Booked on Early Summer Trip

Artemis, the Agency's new advanced telecommunications satellite, is going to be launched in early summer this year, thanks to an agreement between ESA and Arianespace on 17 May. The multi-purpose satellite – the precursor to new and advanced satellite communication services – will be launched by Arianespace on an Ariane-5 from Kourou on 12 July 2001, sharing its trip with the Japanese BSAT-2b direct-broadcasting satellite.

Artemis is ESA's most advanced telecommunication satellite to date. Its orbital position will be maintained by ion propulsion thrusters, a new technology used for the first time on an ESA satellite. Ion engines generate thrust with very high efficiency and as a consequence require significantly reduced amounts of propellant for orbit inclination control. Artemis will also play a significant part in developing Europe's new worldwide satellite navigation system, new mobile communication services and inter-satellite data relay.

The Artemis mobile communication payload includes an L-band Land Mobile

Gaia Summer School, Les Houches, 14-18 May 2001

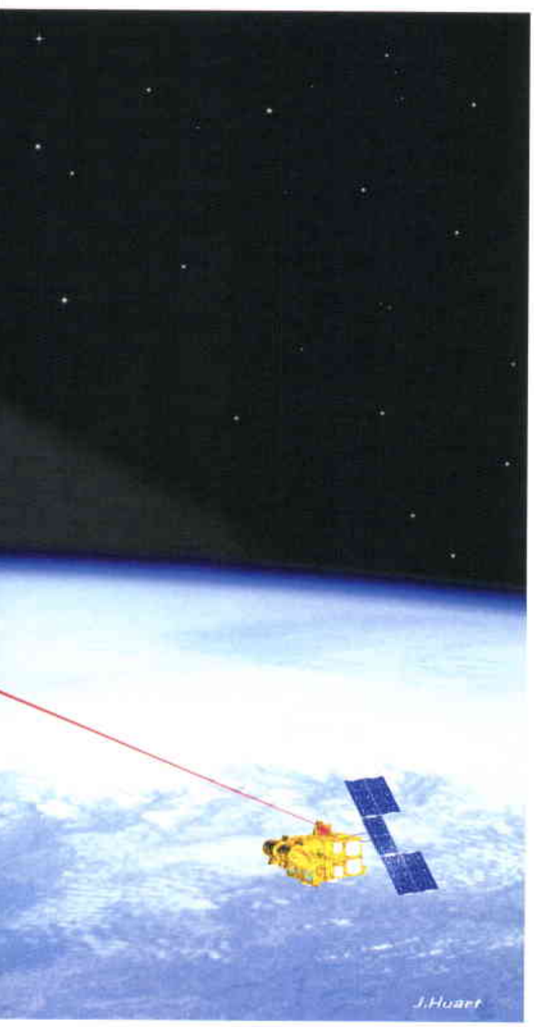
Dozens of young scientists from all over Europe gathered in mid-May at Les Houches in Savoy, France, for intensive briefings on ESA's next star-mapping satellite 'Gaia'. The summer school, part of the prestigious Les Houches series, was organised by Dr Olivier Bienayme (Observatoire de Strasbourg) and Dr Catherine Turon (Observatoire de Paris-Meudon). As the successor to the very successful Hipparcos space-astrometry project, Gaia was approved last year as an ESA Cornerstone mission to be launched around 2010. Engaging the interest and participation of the next generation of astronomers will be vital for the project's success.

ESA's Hipparcos mission (1989-1993) revolutionised astrometry, the science of star measurement, by fixing the positions, brightnesses, colours and intensity variations of more than a hundred thousand stars in our vicinity far more accurately than ever before. Astrometry was previously a difficult subject of interest to only a few specialists in astronomy. Hipparcos changed all that, with results that are still impacting on every branch of astronomy, from comets to cosmology.

Gaia will be 100 times better than Hipparcos. By charting a billion stars, to very much greater distances than Hipparcos, it will give an unprecedented picture of the positions and motions of stars across most of the Milky Way – our Galaxy's equivalent of the Human Genome Project. Besides mapping the three-dimensional structure of our Galaxy, and transforming the science of stars and galaxies, Gaia will be a top discoverer of asteroids and alien planets.

"Gaia will deliver its first results more than ten years from now", notes Dr Michael Perryman, Gaia's Project Scientist. *"Key individuals have already devoted half their working lives to conceiving and accomplishing Hipparcos, and to inventing Gaia. Who'll pick up the baton when they retire? With an impressive line-up of front-ranking European astronomers as lecturers, the Summer School undoubtedly succeeded in inspiring many of the bright young minds that will carry this important science into the future."*

esa



(LLM) facility, with a wide 'Eurobeam', three spot beams and the ability to handle up to 662 voice channels at any one time. This means the satellite will offer unprecedented new facilities for the development of vastly more sophisticated land and marine mobile communication systems. In addition, the satellite has a unique data-relay payload which will speed up communication between satellites and help to bring Earth-observation images down to their appropriate terrestrial stations faster and more efficiently. First to benefit will be the French Earth observing satellite, Spot-4, using the optical section of this payload for a data-transmission experiment called SILEX (Semiconductor laser Inter-satellite Link EXperiment). After its launch later in 2001, ESA's giant Earth 'watchdog' Envisat will communicate data through the Ka-band section of the Artemis data-relay payload.

The Ariane-5 will place Artemis into geostationary transfer orbit, before ground operators at Fucino, Italy assume control of the spacecraft and fire its onboard liquid apogee engine three times to take Artemis to geostationary orbit.

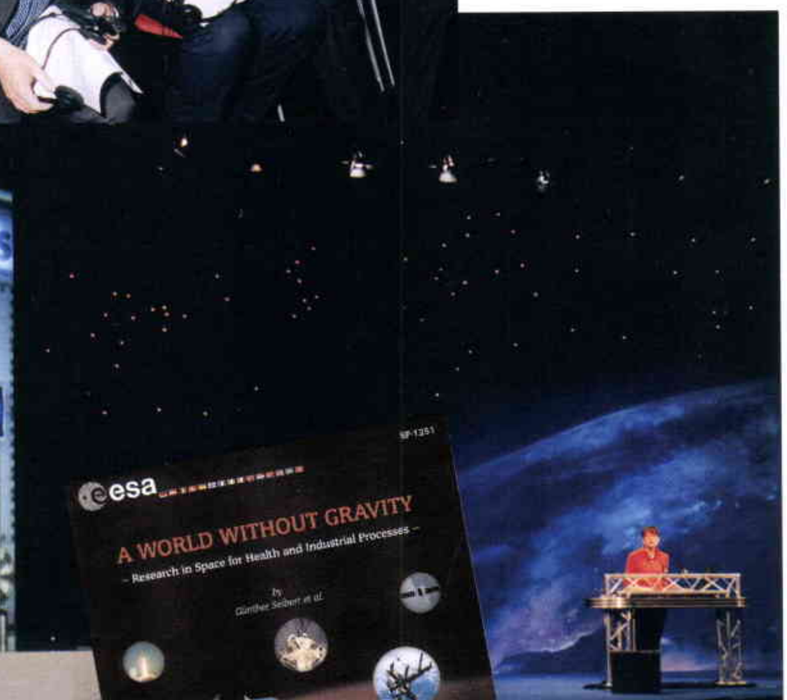
esa

ISS Forum 2001

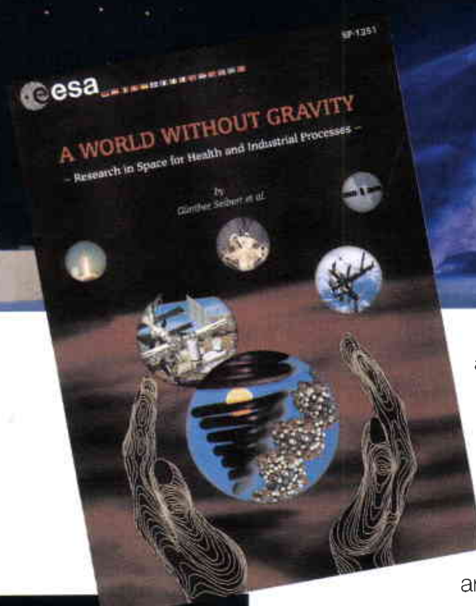
During 5-7 June, Berlin became the focal point for the International Space Station (ISS) when about 800 leaders of industry, government officials and scientists from 22 countries gathered at ISS Forum 2001. This first international conference on Space Station utilisation covered R&D, industrial applications and commercial opportunities, exploring the Station's potential and explaining the opportunities available to users. With the Station now in orbit, the gateway to R&D and commercial use of space is open. Scientists and companies from around the globe have begun to carry out research aboard this unique laboratory, the largest research and technology centre available to date in space. Top-level representatives of the five space agencies involved in the Space Station, namely NASA, Rosaviakosmos (Russia), NASDA (Japan), the Canadian Space Agency and ESA, outlined for the first time their approach to commercialisation of the Space Station.

As a key European minister responsible for space, Germany's Minister for Research and Education, Edelgard Bulmahn opened the Forum. Mrs Bulmahn noted, '*...we intend above all to focus on projects directed at solving real problems on Earth and having potential for new products and applications. As Research Minister, I give*

Preparing for business (from left): Prof. Alain Bensoussan, President of CNES and Chairman of the ESA Council; Mr Antonio Rodotà, ESA Director General; Prof. Walter Kröll, Chief of Executive Board, DLR.



Mrs Edelgard Bulmahn, Germany's Minister for Research and Education, opens ISS Forum 2001.

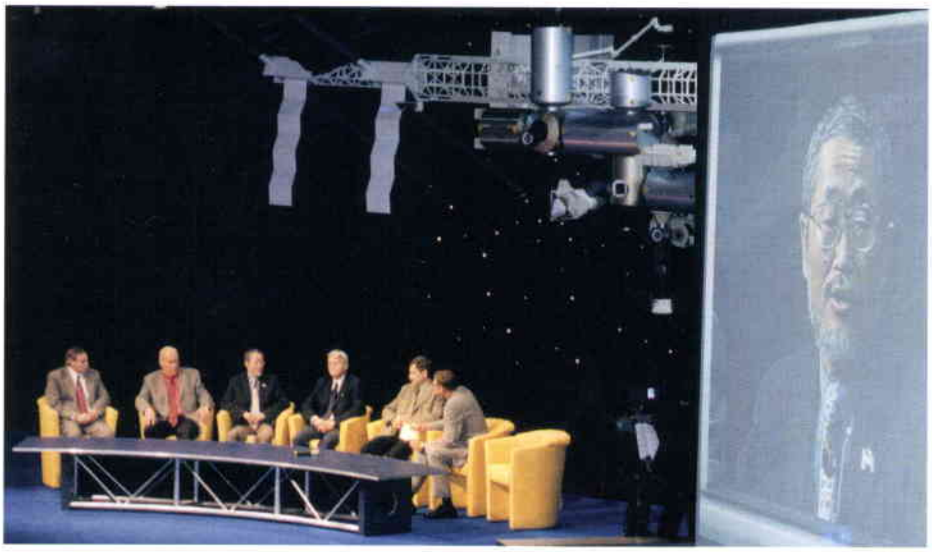


Mrs Bulmahn is presented with copy #1 of ESA's new book on microgravity research by Mr Jörg Feustel-Büechl (right) and Mr Antonio Rodotà.

priority to scientific use of the ISS. But even outside the research domain, many parties have an interest in utilising the ISS in the media, in the entertainment industry, the world of art, marketing. The development and market potential is enormous. That is why I believe we should leave scope for non-scientific commercial ISS utilisation, as long as this does not hinder the scientific effort.'

Mr Antonio Rodotà, ESA Director General, commented that *'... this Space Station is a big instrument for scientists, for industrialists. We hope that from the Station big, big science will come plus new improvements to benefit industry and employment.'*

The Astronaut Roundtable brought together six astronauts to discuss their experiences (from left): Chiaki Mukai (NASDA, on screen), Umberto Guidoni (ESA), Reinhold Ewald (ESA), Bill Readdy (NASA), Julie Payette (CSA) and Frank De Winne (ESA). At far right is Forum moderator Claus Kruesken.



The Roundtable on payload accommodation, integration and processing (from left): Richard Nygren (NASA), Dieter Andresen (ESA), Susumu Yoshitomi (on screen, NASDA), Lawrence Vezina (CSA), Valeri Panchenko (RSC-Energia) and Forum moderator Claus Kruesken.

The first crew to have inhabited the Station – Bill Shepherd, Yuri Gidzenko and Sergei Krikalyov – discussed their life and work onboard from November 2000 to March 2001 and led participants on a tour through 'their Space Station' with the help of 3D virtual reality simulation. A live TV link-up with the Expedition 2 crew currently aboard the Station – Yuri Usachev, Jim Voss and Susan Helms – was a highlight of the Forum, and showed potential users the extensive facilities already in orbit.

Participants also met the Station 'builders' – the companies developing the modules and other hardware – and current 'users' – companies in areas ranging from hi-tech to media that are already benefiting from being onboard.

The final day was largely devoted to roundtables on access policy for institutional users and commercial customers, and the handling of payloads.

The conference also saw ESA signing its first contract to provide resources to commercial users. Mr Jürgen von der Lippe of Intospace and Mr Jörg Feustel-Büechl, ESA Director of Manned Spaceflight and Microgravity, signed a 2 million Euro contract for the Agency to supply a proportion of its allocation of Station resources. ESA now has an open call for commercial proposals, accessible at
<http://www.esa.int/spaceflight/isscommercialisation>

The next issue of ESA's *On Station* newsletter will be devoted to the Forum.

esa

Thomas Reiter, Sergey Krikalyov and Yuri Gidzenko (on stage, with moderator Claus Kruesken) link up live with the ISS.

The Kids from Mars City

The heart of a city on Mars would be a scientific laboratory. You need water supply tanks and an oxygen factory and straw tubes to transport water and air, you need a windmill of course and a cable car, also a volcano and a rocket launcher... at least that is what a Mars city looks like in the imagination of 32 kids from the Groenhorst Chr. Basisschool in Leusden. They won the Space Kwispel Competition for which Dutch schoolchildren between ten and twelve years of age were asked to design and build a Martian City out of the sponsor's – milk company Melkunie – milk packages. 50 different classes thought up interplanetary football matches (Mars FC vs Jupiter FC), lasers to melt ice caps for water generation, MarsDonalds restaurants, and many other lovable details. The winning class came to ESTEC on 22 March for a Space Day – with space related prizes, real space scientists, engineers and even astronauts Wubbo Ockels and André Kuipers to talk to, satellites, the Space Expo, and the Dutch entertainer Peter Jan Rens – alias Menheer Cactus – as a host.

"It's a great thing for the children," said their teacher Mia Rap while her class – all in T-Shirts with the Mars City logo – explained the set-up of the city and introduced the different working groups they had set up to build their city model (design, information, construction...) to Peter Jan Rens and Wubbo Ockels. *"Normally it is quite a difficult class. Building the Mars City together has shown them how much they can do when they cooperate, and that they even won the competition has given them a good experience of co-operation and success. They've done a wonderful job and deserve it well,"* she added.

In February almost all elementary schools in the Netherlands had received a Space Kwispel competition package with the school milk. The Space Kwispel is a quiz game about space developed by ESA's Education and Outreach Office in collaboration with the Dutch toy company "King International" and ESA's Publications Division. esa

'Industry Space Days' Foster Collaboration between SMEs and ESA

The "Industry Space Days", held at ESTEC on 9 and 10 May, were a great success. More than 570 participants representing 330 European and Canadian companies attended the ISDs. ESA organises this event to foster exchanges between Space Agencies, established space groups and Small and Medium-sized Enterprises (SMEs). The initiative encourages SMEs to take a more active part in the European space programmes, explaining to them how to do business with ESA and its major industrial partners and giving them the opportunity to meet other potential customers and establish new co-operation schemes.

This year, the ISD 2001 proposed a whole range of conferences tailored to inform SMEs and trained them in different areas related to space requirements and best practices for successful business in general. ESA programmes and their related business opportunities, as well as the business opportunities within National Agencies and some of the large space groups such as Astrium, Alenia, and Alcatel were also presented. The SMEs displayed their expertise and fields of specialisation in dedicated exhibitions and workshops to discuss business-related subjects.

In addition, in more than 2000 business meetings SMEs and other potential partners discussed business opportunities and possible co-operation. The Industry Space Days, organised by ESA's SME Unit on a two-yearly basis, once more proved to be extremely useful for all participants. esa

Exploring the Whole of the Moon...

The Lunar Explorers Society (LUNEX), an international organisation founded last year at ESTEC by 200 Moon enthusiasts, held its first Convention, in Paris, from 8 to 10 March. The more than 80 delegates – professionals, amateur space enthusiasts and interested visitors from the public – came together to discuss the Moon in all its facets.

Participants talked about the colonisation of the Moon, its use as a scientific laboratory, e.g. for geology or as an astronomical platform, the knowledge of lunar geography needed to land and move on the surface, the implications of finding water-ice on the Moon and whether this might be detected by forthcoming missions, and the architecture of lunar habitats, to give only a few examples. Would you have thought that the flower most likely to grow on the Moon would be the tulip? Or that the Society thinks that by the year 2040 (with intermediate steps via Moon lander, robotic village and lunar base) there will be a human village on the Moon? Several groups – among them the Young Lunar Explorers – also presented their outreach activities and gave recommendations for future educational projects involving the Moon. The Society's driving question – whether it will be possible to transform that barren landscape 384 000 km away into a thriving hub of scientific research and industrialisation – will remain unanswered for the time being, but Bernard Foing, chairman of the LUNEX Society, and the LUNEX members see it as a big step in the right direction.

The Convention was also the main public event in 2001 at which SMART-1 was presented. Due to be launched in 2002, SMART-1 will test solar electric propulsion and other innovative approaches for future deep space probes. It is the first European satellite to be sent towards the Moon. A SMART-1 model was on display at the conference venue, the Palais de la Découverte in Paris.

LUNEX was founded at the end of the 4th Conference on Exploration and Utilisation of the Moon (ICEUM4), organised by ESA and the International Lunar Exploration Working Group (ILEWG) in July 2000. Its aim is to promote the exploration of the Moon for the benefit of humanity, bridging the gap between space agencies and the general public to promote planetary exploration and space.

...and Flags for the Whole World

10-year old Anna Moloney from Ireland has painted a yellow flag with three clear symbols: blue wavelines for water, a green tree for life and nature, and a red human figure. *"The yellow background symbolises the Sun. It is in the background because the Sun is the reason for all life and activity on Earth"*, Anna explains. She participated in ESA's Earth Flag competition and won the Irish competition. Anna and the 15 other national winners will be at the Paris Air Show at Le Bourget, where the ultimate winner was announced on 17 June. She is 12-year old Anke Hartmanns from Germany (3rd line, leftmost flag), who drew a flower representing the Earth and Envisat watching over it. The winning picture will circle the Earth on Envisat. As the satellite observes the Earth, the idea was to design a flag that represents the whole of our planet. More than 11000 children from the ESA Member States and Canada sent in their artwork, accompanied by short texts to explain the layout, colours and symbols.

14 Experiments on the Busiest Ever Parabolic Flight Campaign

The 30th ESA parabolic flight campaign was the busiest ever. Three flights of 30 parabolas each on the special Airbus A300 Zero-g started from the Bordeaux-Mérignac airport on the mornings of the 15, 16 and 17 May.

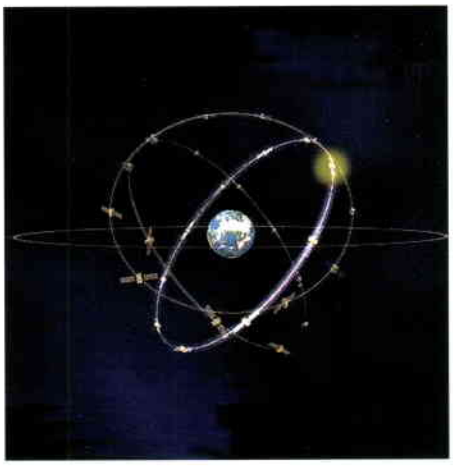
ESA organised this campaign to conduct research experiments in almost complete absence of gravity (microgravity) to prepare future experiments for the International Space Station. This 30th campaign since 1984 is the largest ESA campaign ever in terms of number of experiments: fourteen experiments including eight in Physical Sciences, three in Life Sciences, and three experiments proposed by students.

During a parabolic flight the aircraft performs a nose-up manoeuvre to put it into a steep climb. This creates an acceleration of 1.8 g (1.8 times the acceleration due to gravity on the ground) for about 20 seconds. Then the pilot reduces engine thrust to almost zero, injecting the aircraft into a parabola. The plane continues to climb till it reaches the apex of the parabola, then it starts descending. This condition lasts for about 25 seconds, during which the passengers and all unstrapped equipment in the cabin float in the weightlessness resulting from the free fall of the aircraft. When the angle below the horizontal reaches 45°, the pilot accelerates again and pulls up the aircraft to return to a steady horizontal flight. These manoeuvres are usually repeated 30 times per flight.

During the weigthlessness periods, the scientist on board the aircraft can conduct their experiments. With Europe and its international partners building the International Space Station, parabolic flights are crucial to the preparation of experiments, equipment and astronauts and allow scientists to have their experiments tested before they are actually flown on a space mission.

The next ESA parabolic flight campaign (the 31st) is scheduled for October 2001. This campaign will have a mixed complement of experiments in Life and Physical Sciences, again with student-proposed experiments. esa

Galileo Approved at EU Level



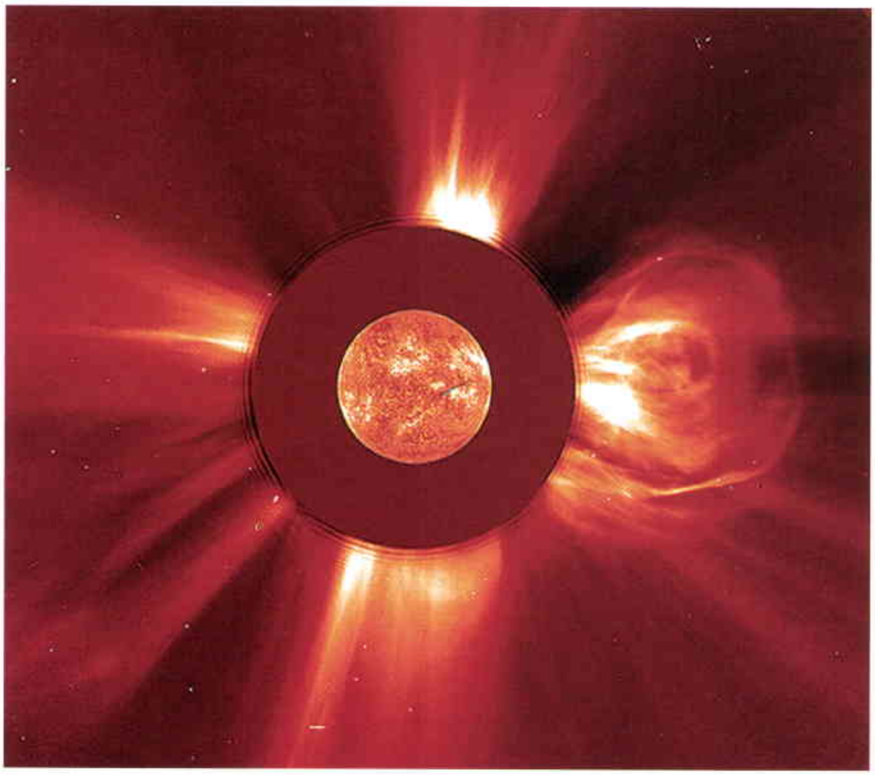
The Transport Ministers of the European Union approved the Galileo programme on 5 April at the Council meeting in Luxembourg. They agreed to go ahead with the development and validation phase for Galileo and make available 100 million Euros. The European satellite navigation system will provide a highly accurate global positioning service under civilian control. It will be inter-operable with the two other global satellite navigation systems GPS and GLONASS.

The 30 Galileo satellites are scheduled to be in their circular orbits some 24 000 km above the Earth by the year 2008, delivering positioning accuracy down to four metres. The 2900 million Euro project will be financed through a public/private partnership between the European Commission, ESA and private industry.

At their next meting in December, the Ministers are expected to release another 450 million Euros and approve the creation of a programme management. At their meeting on 5 April they also agreed to take the formal decision on the deployment of the full Galileo constellation by the end of 2003. esa

5 Years of Discoveries with SOHO

What an appropriate day for the anniversary of a spacecraft that watches the sun: SOHO's 5th anniversary on 27 April coincided with the celebration of Sun-Earth Day 2001, by the European Space Agency, NASA and other agencies. In April 1996 the European-built SOHO was commissioned, and the observations with a dozen sets of clever solar instruments formally started at that time. The day also marked the opening of the observations of SOHO's SWAN and MDI instruments to the public. One sees ultraviolet rays sweeping like a beam across interplanetary gas beyond the Sun, while the other locates hidden sunspots and their active regions. Both watch the far side of the Sun and help predict active regions and eruptions from the Sun a week before it turns towards Earth. Scientists from 62 institutes in 15 countries work in the teams that provide and operate SOHO's instruments. Weighing 1.85 tonnes at launch, it was dispatched by a NASA rocket on 2 December 1995, and transferred to the vicinity of Lagrange Point No. 1, where it now hovers, 1.5 million kilometres from the Earth.



In its five years of gathering solar data, the observations made and conclusions drawn form a long story of success. SOHO examines the Sun from a vantage point 1.5 million kilometres out, on the sunward side of the Earth. Its instruments probe the Sun from its nuclear core, through its turbulent interior and stormy atmosphere, all the way out to the Earth's orbit and beyond, where a non-stop stream of atomic nuclei and electrons travels outwards as the solar wind. To the naked eye the Sun looks calm and unchanging, but for SOHO it has performed a dramatic striptease. Here are a few of the revelations:

- Currents of gas far beneath the visible surface speed up and slacken again every 16 months - a wholly unexpected pulse-rate. It was detected by combining data from SOHO and a US-led network of ground stations called GONG.
- Watching minute by minute and year by year, SOHO has seen the Sun brighten, as expected, by 0.1 percent while the count of sunspots increased during 1996-2000. By studying the variations in detail, scientists estimate that high-energy ultraviolet rays from the Sun have become 3 percent stronger over the past 300 years.
- Most of the explosive outbursts of gas from the Sun, called coronal mass ejections, miss the Earth. Only SOHO can reliably identify those heading in our direction, by linking expanding haloes around the Sun to shocks seen in the Earth-facing atmosphere. Engineers then have 2-3 days warning of possible effects in the Earth's vicinity.
- A reason why the Sun's atmosphere is far hotter than its visible surface is a non-stop succession of small explosions, observed by SOHO. They result from a continual rearrangement of tangled magnetic fields.
- SOHO sees gas leaking from the corners of a magnetic honeycomb of gas bubbles, mainly in polar regions, to supply a fast solar wind. Nearer the Sun's equator, a slow wind escapes from the edges of wedge-shaped features called helmets.
- Charged atoms feeding the fast wind gain speed very rapidly – evidently driven by strong magnetic waves in the Sun's outer atmosphere. Similar magnetic waves may accelerate the slow wind too, although many mass ejections also contribute to it.
- SOHO detected phosphorus, chlorine, potassium, titanium, chromium and nickel for the first time, and previously unseen isotopes of six commoner elements. These give clues to conditions on the Sun, and also to Solar-System history.
- After a solar flare, SOHO sees waves rushing across the Sun's visible surface, like the ripples seen when a stone falls into a pond. One such event was judged to be 40 000 times more energetic than the San Francisco earthquake of 1906.
- SOHO has discovered tornadoes as wide as Africa, with hot gas spiralling outwards from the polar regions of the Sun. Typical wind speeds of 50 000 kilometres per hour can become ten times faster in gusts.
- A wind of gas from the stars blows through the Solar System, and the solar wind fights it. SOHO has fixed its direction (from the Ophiuchus constellation) and its speed (21 km/s) more accurately.

More than 3600 coronal mass ejections from the Sun have been observed by SOHO's LASCO instrument, making an average of two per day during SOHO's five years of observations. It saw the biggest solar flare that has ever been recorded on 2 April this year – it hurled a coronal mass ejection into space at 72 million kilometres per hour. SOHO is also by far the most prolific discoverer of new comets in the entire history of astronomy. By mid-April 2001 the number stood at 304, most of them being small comets that fall into the Sun. Amateur astronomers around the world examine SOHO's pictures via the Internet, and have been first to spot more than 200 of the SOHO comets.

Watch that Debris

If you are concerned about the more than 8000 pieces of space debris – some of them as big as a car – that are orbiting the Earth, the third European Conference on Space Debris from 19 to 21 March at ESOC, ESA's European Space Operations Centre in Darmstadt, Germany, would have been the place for you. It drew over 200 experts on space debris from all over the world to discuss a large number of topics related to the inactive spacecraft, ejected boost motors, fragments of satellite and rocket stage breakup, and all the other metallic bits of shields, booms, covers and caps that are floating in space.

ESA hosted the conference, while the British, French, German and Italian space agencies (BNSC, CNES, DLR, ASI), the Committee on Space Research (COSPAR), and the International Academy of Astronautics (IAA) co-sponsored it.

While the use of space is expanding in nearly all areas – e.g. telecommunication, navigation, Earth observation, science – space debris is of growing concern as a threat to both manned and unmanned spaceflight. The purpose of the conference was to provide a forum for presentations of results on research topics ranging from ground- and space-based techniques for detection of orbital debris, trends in the orbital debris environment in Low Earth Orbit and the geostationary ring, the design of protective shields, to the removal of debris by tethers. The aspects discussed included methods and computer tools to predict the growing number of man-made objects in space, analysis of material returned from space, risks run by satellites in low-Earth and geostationary orbit, risks on the ground from reentering objects, standards addressing safety and mitigation of space debris, and legal issues. esa

New Building Inaugurated at INTA-Spasolab

INTA-Spasolab, ESA's external laboratory for solar-cell qualification and testing in Madrid, has a new building that was formally inaugurated on 17 May. The new building considerably increases the capabilities of Spasolab (Space Solar Cell Test Laboratory), formally set up at INTA (Spain's Instituto Nacional de Tecnica Aeroespacial) in 1989. INTA is one of the technological institutes of the Spanish Ministry of Defence with a long tradition and experience in space activities in European and Spanish projects.

The inauguration started with a general presentation on INTA and its technical capabilities and ended with a guided tour of the new facilities. Representatives from ESA and the national space agencies (CNES, DERA), space industry (Astrium, Fokker, CASA, ASE, CESI, ENE, Rimsa, CRISA, etc), photovoltaic R&D institutes (IES, Ciemat, Fraunhofer-ISE) and terrestrial photovoltaic industry (BP Solar, Isofoton, Censolar) had the opportunity to study the new facilities first hand. One of the main testing areas in this new building was named "Bogus/Larue" as a tribute to ESA staff members Klaus Bogus and Jean-Claude Larue, who have been involved in the setting-up of Spasolab since the early eighties.

Spasolab carries out qualification of solar cells for specific space missions and characterises space solar cells under development by industry and photovoltaic research institutes. Spasolab also performs electrical and environmental characterisation of solar coupons and panels, as well as research and development on testing methods for new types of space solar cells. esa

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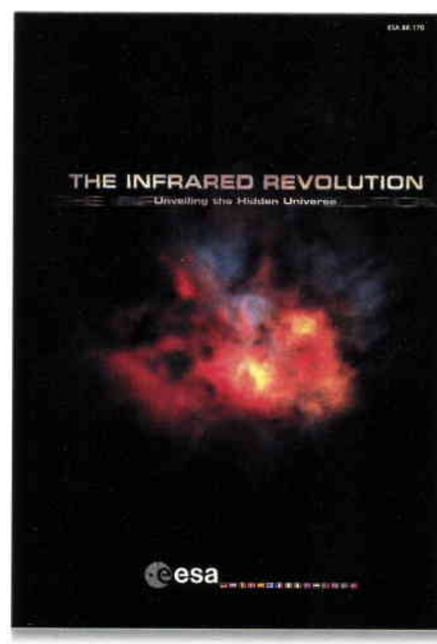

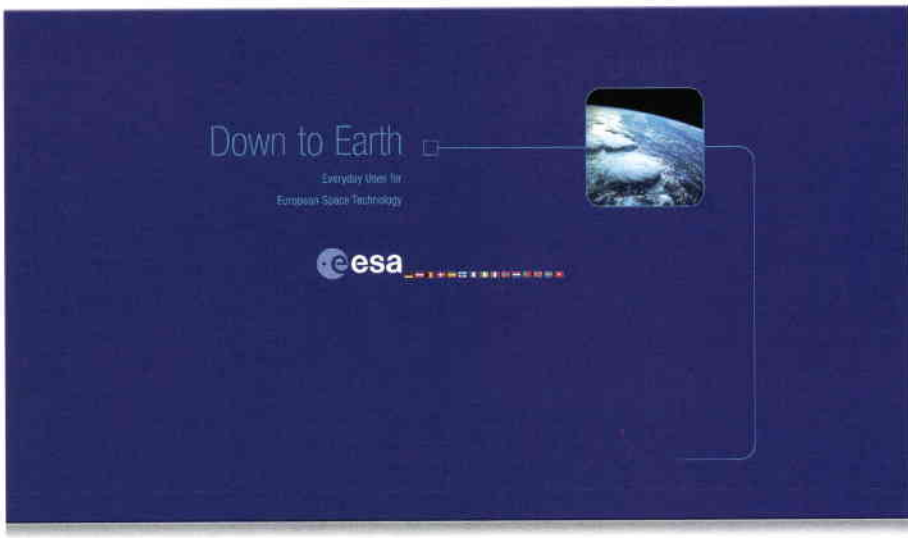

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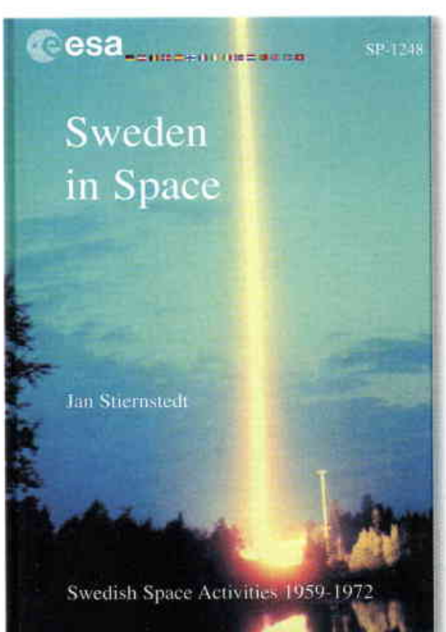

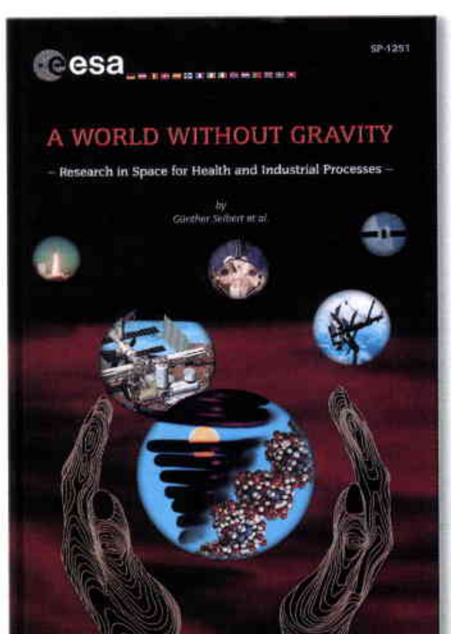

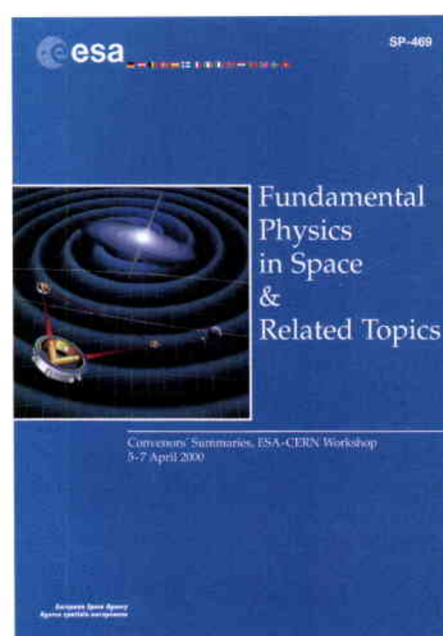

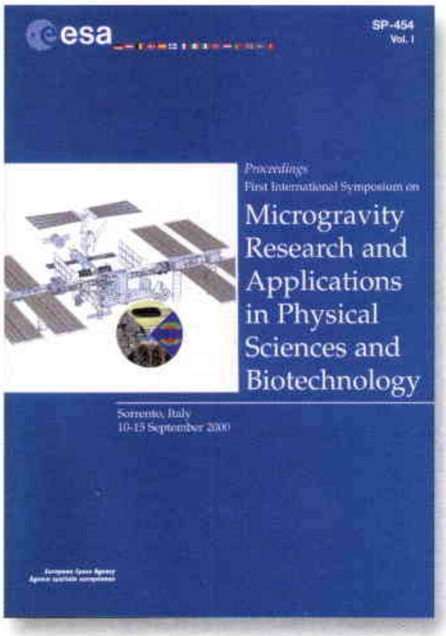

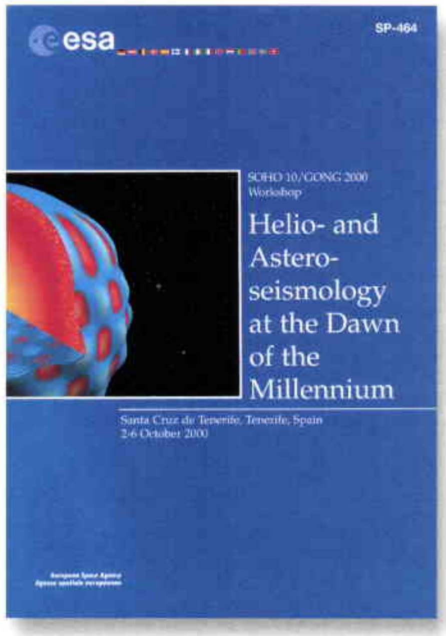

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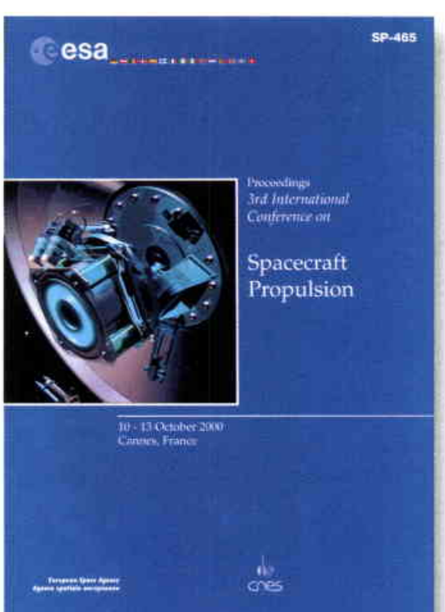

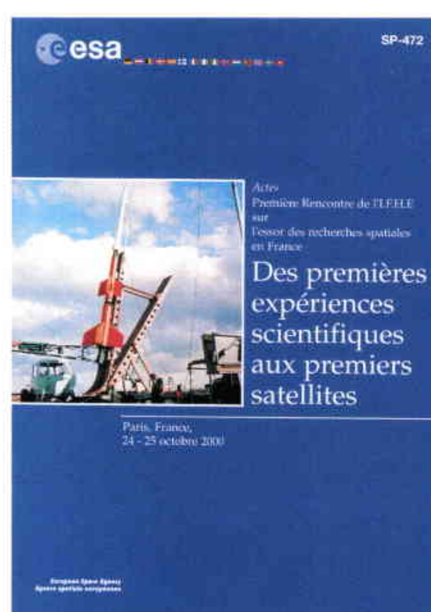

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