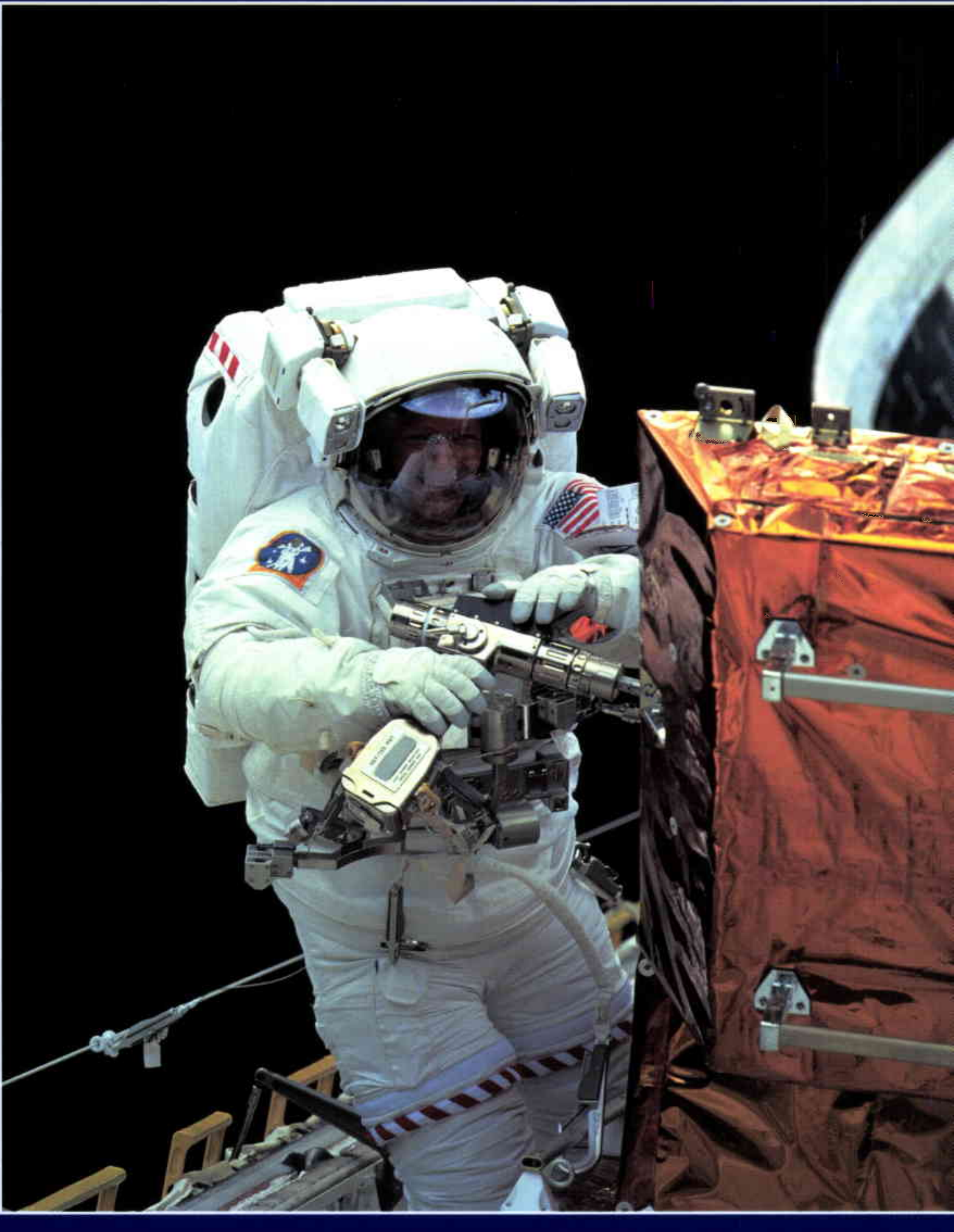
esa bulletin

number 104 - november 2000



European Space Agency
Agence spatiale européenne

european space agency

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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.

The major establishments of ESA are:

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

ESRIN, Frascati, Italy.

Chairman of the Council: A. Bensoussan

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agence spatiale européenne

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

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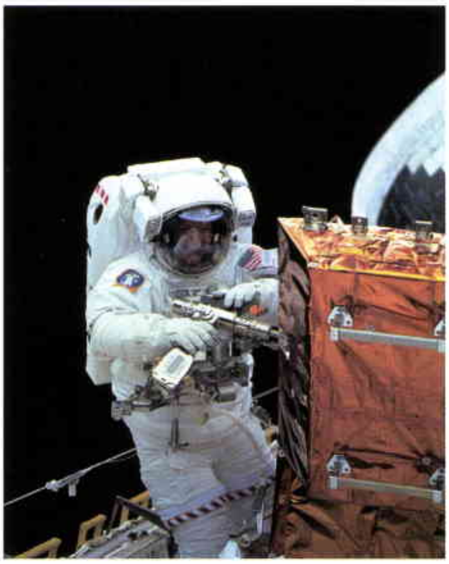

Cover: ESA Astronaut Claude Nicollier at work on the Hubble Space Telescope in December 1999 (see pages 10 and 136 of this issue).

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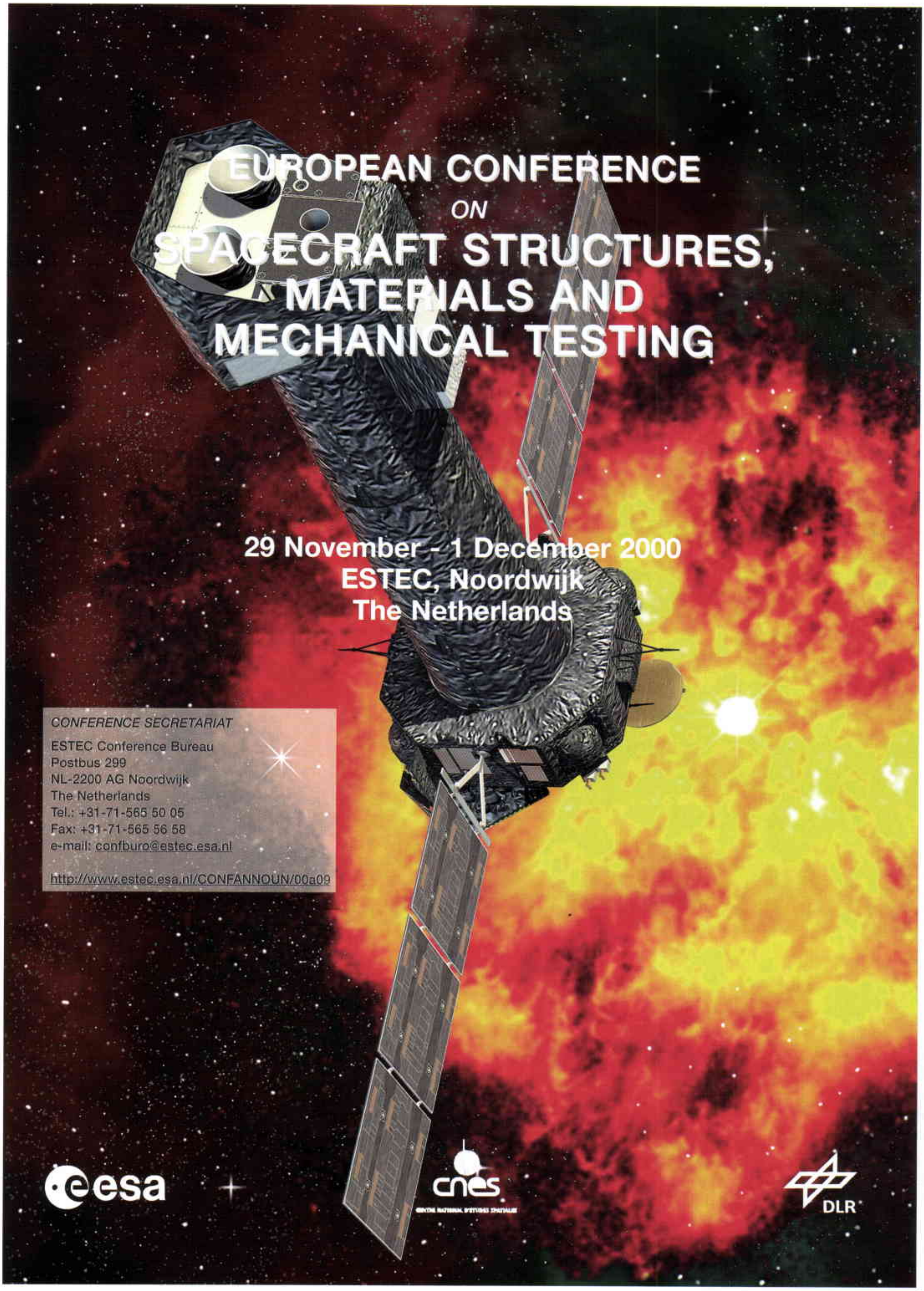
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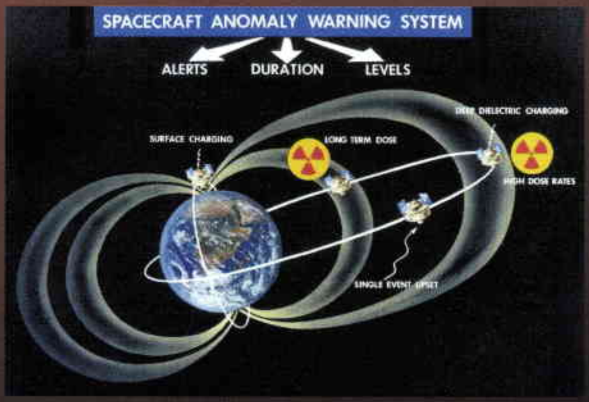

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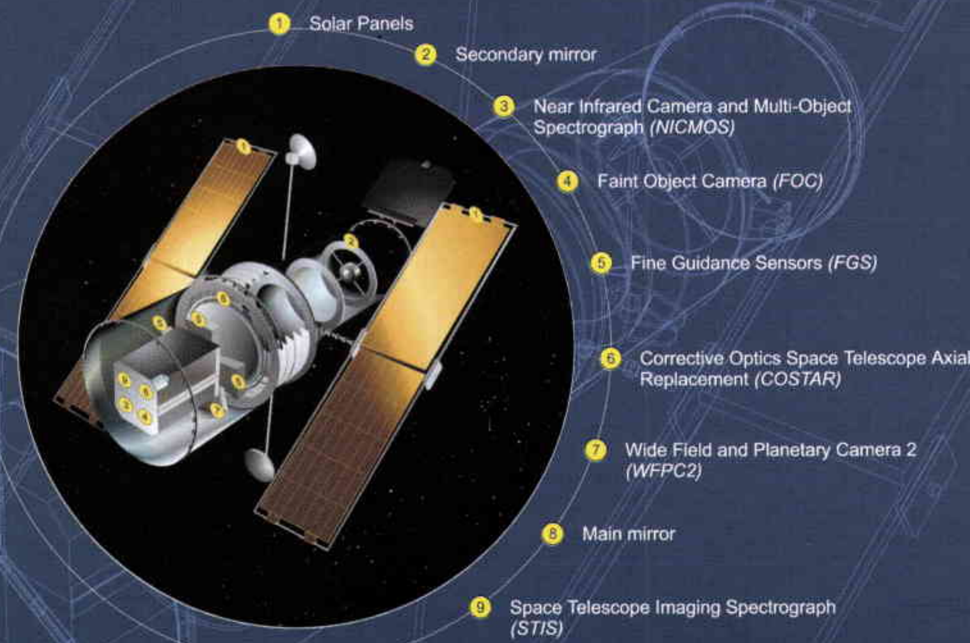
Hubble Space Telescope



The Instruments

The complement of instruments onboard Hubble – 2 cameras, 2 imaging spectrographs and a set of 3 fine guidance sensors – enable a wide variety of observations to be made.
The second Wide Field/Planetary Camera (WFPC2) is the primary camera on Hubble. It is capable of imaging the sky through a wide range of filters extending from a wavelength of 1000 nm in the near infrared to 115 nm in the ultraviolet.

The Spacecraft

Primary mirror — *Ritchey-Chrétien optics*	*2.4 m*
Total length	*15.9 m*
Diameter (solar panels stowed)	*4.2 m*
Solar panel span	*12.1 m*
Weight	*11,110 kg*
Pointing accuracy	*7 milliarcseconds for 24 hrs*

The Orbit

Altitude (original)	*598 km*
Inclination to the equator	*28.5 degrees*
Mission lifetime	*20 years (until 2010)*

More general and technical information about the NASA/ESA Hubble Space Telescope can be found at the
Hubble European Space Agency Information Centre: **http://hubble.esa.int**

The Hubble Space Telescope – 10 Years On

P. Benvenuti & L. Lindberg Christensen
ESA/ESO Space Telescope European Coordinating Facility, Garching, Germany

Last Christmas Eve was very special one for ESA astronauts Claude Nicollier and Jean-François Clervoy: together with their American colleagues, they spent it aboard the Space Shuttle 'Discovery', after concluding the latest scheduled repair mission to the orbiting Hubble Space Telescope (HST). This third Shuttle refurbishment mission to HST was, like its two predecessors, a resounding success. Only days later, as Hubble entered the new millennium, came the first beautiful images of a complex gravitationally lensing cluster of galaxies.

The astronauts' visit took place shortly before the 10th Anniversary of the launch of Hubble, which was first placed in orbit on 26 April 1990. Since then, HST has become the leading tool in ultraviolet, optical and near-infrared astronomy and is now looking forward to another decade of exciting discoveries and sharp views of the Universe.

Introduction

ESA is NASA's partner in the Hubble Space Telescope Project. ESA built the Faint Object Camera (the HST instrument that delivers images with the highest spatial resolution), provided the solar panels that power the spacecraft, and supports a team of 15 scientists at the Space Telescope Science Institute in Baltimore (STScI), USA. In return, a minimum of 15% of the Telescope's observing time is guaranteed for projects and research submitted by European astronomers from ESA's Member States. In reality, the high standard of projects from European astronomers has, so far, won them some 20% of the total observing time.

The initial ESA/NASA Memorandum of Understanding on HST expires 11 years after its launch, i.e. in April 2001. Both ESA and NASA are convinced that the collaboration on HST has been very successful, not merely in the development and initial operation of the Telescope, but also, more significantly, during its scientific operation. ESA astronomers have had access to a unique facility and the project as a whole has benefitted from the European intellectual contribution. A 'concept agreement' for the continuation of the collaboration, including a possible participation in the Next-Generation Space Telescope, has already been signed.

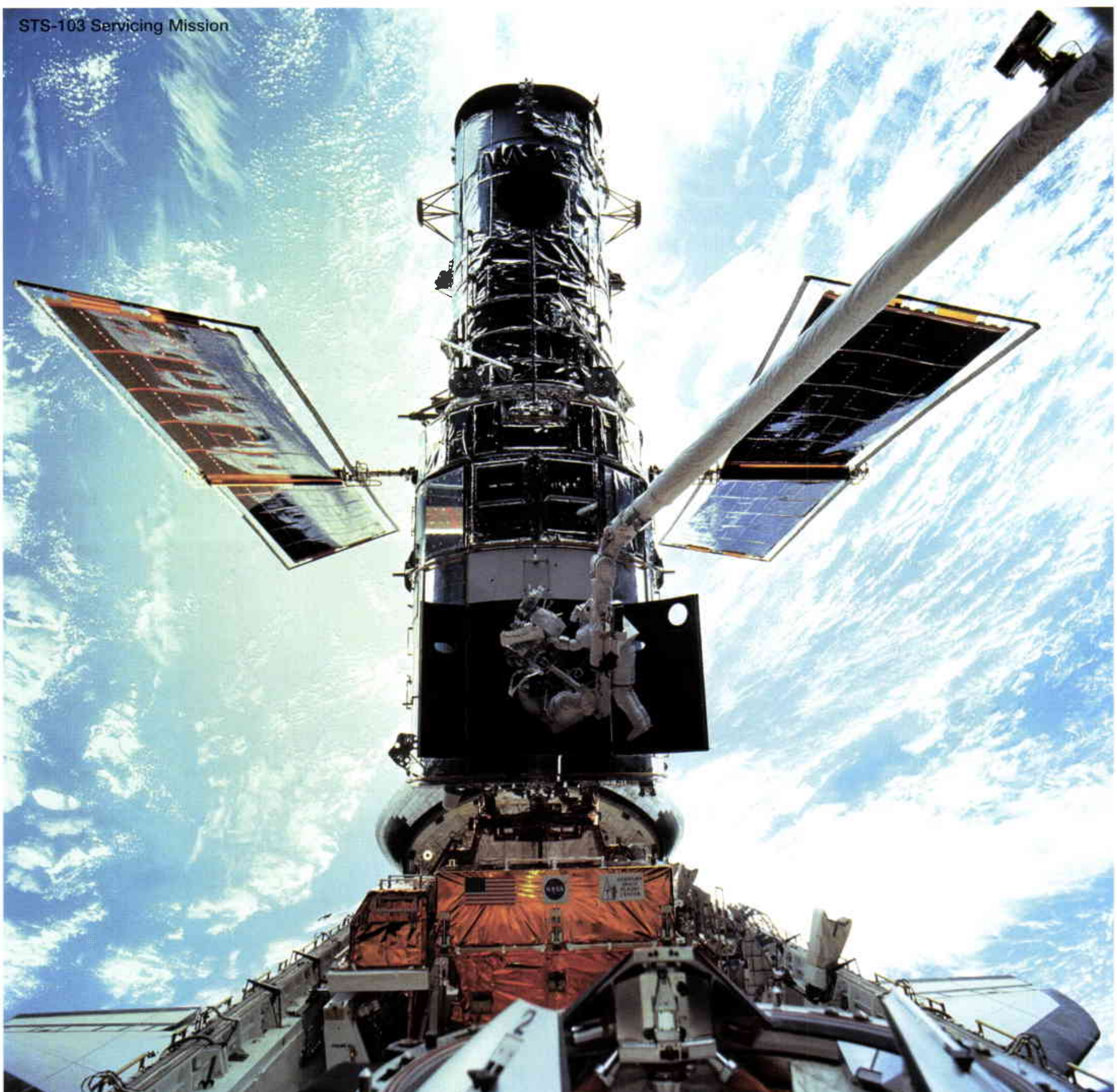
Abell 2218 (WFPC2)

European astronomers receive assistance from the Space Telescope European Coordinating Facility (ST-ECF) in Garching, near Munich, Germany. The ST-ECF, jointly operated by ESA and ESO, the European Southern Observatory, provides support in the calibration and analysis of HST data, and maintains and offers to the community the scientific archive of HST images and data.

The Servicing Missions

Servicing Missions that continuously keep the observatory and its instruments in prime scientific condition are one of the innovative ideas behind Hubble. Initially, telescope maintenance visits were planned for every 2.5 years and a larger overhaul was envisaged every five years, when HST would have been brought back to the ground. This plan has changed somewhat over time and a servicing scheme that includes Space Shuttle Servicing Missions every three years was finally decided upon.

The first two Servicing Missions – in December 1993 (STS-61) and February 1997 (STS-82) – were very successful. In the first three years of operation, HST was not able to meet expectations because its primary mirror is 2 microns too flat at the edge. This defect was discovered only after launch and initially caused severe consternation amongst the scientific community and the general public. However, the first Servicing Mission in 1993 (on which the European astronaut Claude Nicollier flew)



corrected for this problem by installing a new instrument with corrective optics (COSTAR - Corrective Optics Space Telescope Axial Replacement). This pair of 'glasses' opened the way to HST's golden age. The images were at last as sharp as originally hoped for, and new, astonishing results started to emerge on a regular basis. On the first Servicing Mission, the solar panels were also replaced and a new camera was installed (Wide Field and Planetary Camera 2 - WFPC2). The High-Speed Photometer (HSP) was replaced by COSTAR.

During the second Servicing Mission, instruments and other equipment were repaired and updated. The Space Telescope Imaging Spectrograph (STIS) replaced the Goddard High-Resolution Spectrograph (GHRS), and the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) replaced the Faint-Object Spectrograph (FOS).

The third Servicing Mission was initially intended to replace the ESA Faint-Object Camera (FOC) with the new Advanced Camera for Surveys (ACS) and to install a cryocooler on the infrared instrument NICMOS in order to extend its operational lifetime. Furthermore, the solar arrays, as well as many other subsystems, were scheduled for replacement. As the mission schedule filled with ever more tasks, the gyroscope system that Hubble uses to maintain its orientation began to show signs of failure. Without the help of the gyroscopes, HST would have to be kept in a fixed, safe orientation and scientific operation would have to be suspended. It was therefore decided to split the third Servicing Mission into two parts (SM3A and SM3B), with the first mission aimed at replacing the gyroscopes as soon as possible, thus postponing the installation of the new instruments to SM3B. This was a wise decision, since the gyroscopes did indeed fail just a month before SM3A.

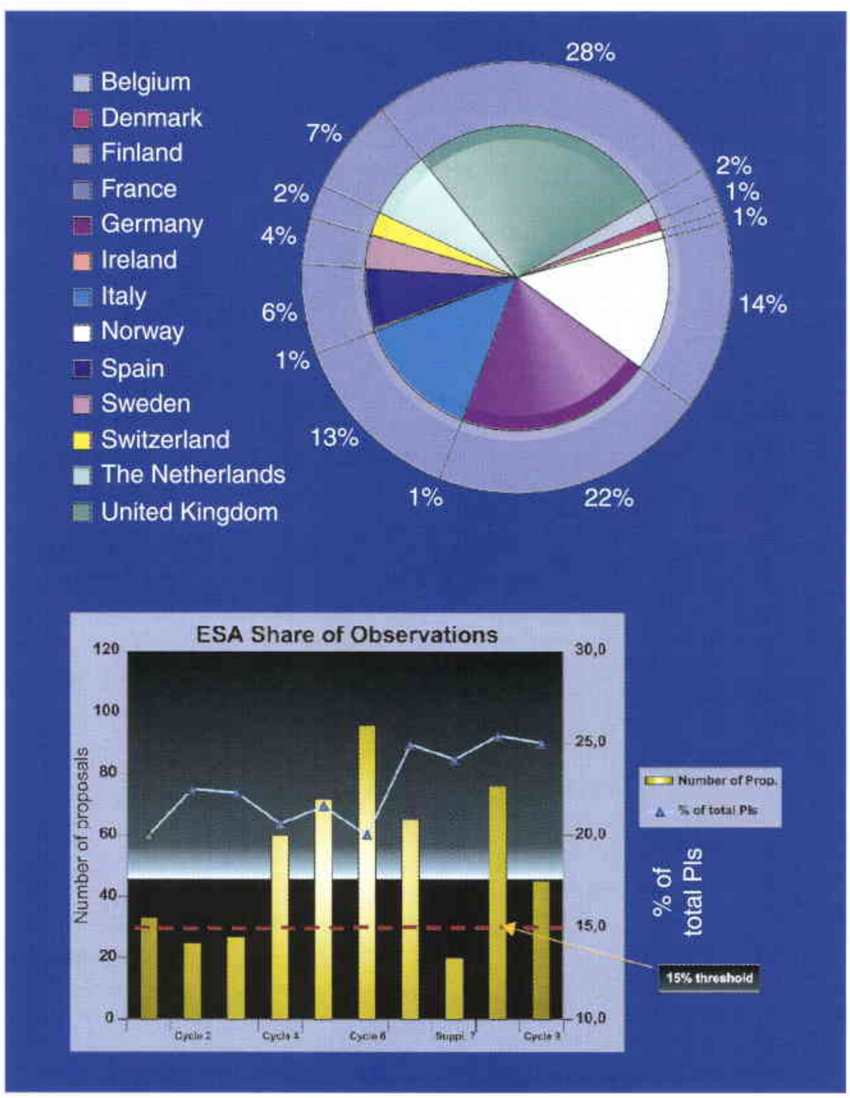
SM3B is now scheduled for late 2001 and a 4th, final servicing visit is planned around 2004, during which a new UV spectrograph (COS - Cosmic Origins Spectrograph) will be installed, together with a refurbished Wide-Field Camera (WFC3). After this, HST will continue to be operated, but on a reduced-cost basis, for as long as it continues to produce useful scientific results, possibly up to and beyond 2010 when its successor, the Next-Generation Space Telescope, should be ready to pick up the HST legacy.

The first 10 years of HST have demonstrated how significant the concept of Servicing Missions has been for the continued efficient operation of such a sophisticated telescope.

Not only was the initial mirror problem, which would otherwise have meant the 'sudden infant death' of HST, promptly corrected, but new and continuously improved instruments were installed, ensuring that HST has remained competitive with the fast-evolving arena of ground-based astronomy.

Europe and Hubble

As already mentioned, the contribution of ESA to the Hubble project guarantees European scientists access to 15% of Hubble observing time. This time is allocated on pure scientific merit by an international panel that includes European experts. Ever since HST scientific operations began, European astronomers have been allocated more than the guaranteed 15% threshold, and in recent years the fraction of time allocated to European scientists has been close to a quarter. Scientists from most ESA Member States have had an opportunity to observe with Hubble. During the first 9 cycles, more than 850 European astronomers were Principal Investigators (PIs) or Co-Investigators (CoIs) in at least one successful Hubble observing programme, and many were investigators in many cycles.



The ESA participation in the Hubble project has an importance for European astronomy over and above the numbers and statistics: it provides the opportunity to use a World-class observatory of a kind that Europe alone would not have been able to build and operate. Thus, it has enabled scientists in Europe to continue to be competitive and even to lead in several areas of astrophysics and cosmology.

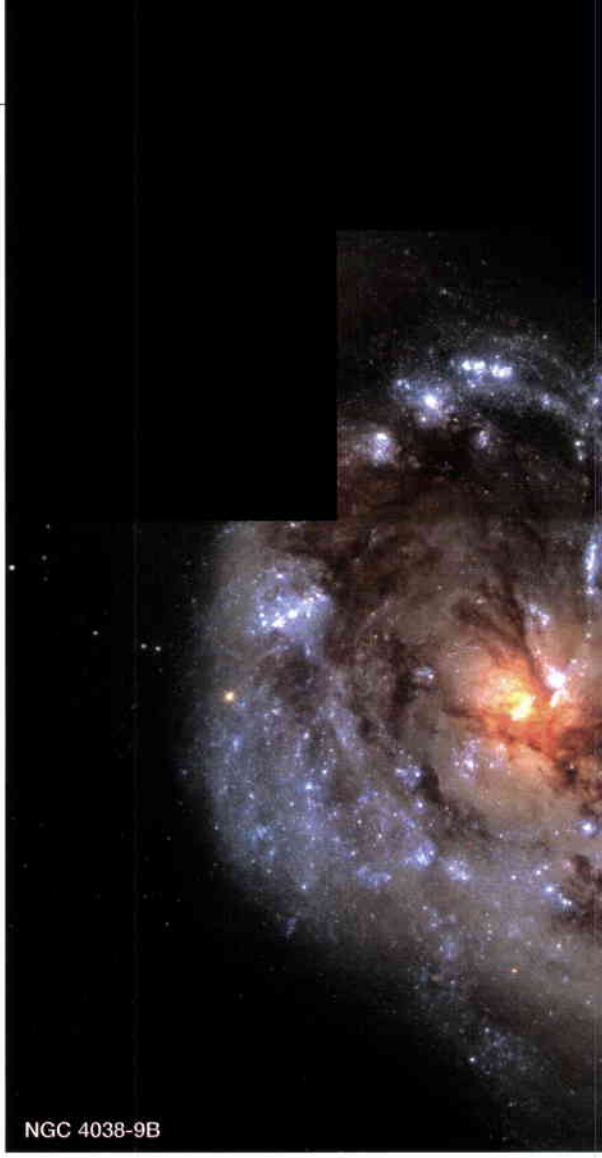
Hubble science

Ten years of exciting Hubble observations are not easy to summarise in a short article. We can only give a small sample of the science from HST here, highlighting, perhaps, areas where Hubble has influenced the research development most dramatically.

Firstly, Hubble is unique because of its unprecedented high resolution over the entire field of view. It has been debated recently that the best placed ground telescopes – some of which have much larger collecting areas than HST, such as the Very Large Telescope or the Keck Telescopes – can reach diffraction-limited PSFs (Point Spread Functions) using a technique called active optics. Active-optics systems rely on a fast-reacting optoelectronic surface to correct for the wavefront distortion introduced as light passes through the atmosphere to reconstruct the original wavefront and thus produce diffraction-limited images. However, this technique works only for a very limited field of view – a few seconds of arc in radius – while a space telescope like HST is only limited by its own optical aberrations. To give an example, the new Advanced Camera for Surveys on HST has a field of view of 202 $arcsec^2$. HST is still the only telescope able to render images of extended objects, such as galaxies and nebulae, with the same superb resolution of 0.05 arcsec over the whole field.

Secondly, HST has the ability to extend its observations to wavelength ranges that are either inaccessible from the ground – like the UV region from 330 to 115 nm – or are heavily disturbed by the atmosphere – like the near-IR range from 0.8 to 2.5 micron.

These two fundamental properties of Hubble, together with the lower sky background noise that is achievable above the Earth's atmosphere, make it a unique instrument. HST is not only able to make its own discoveries and pursue its own lines of research independently, it is also capable of stimulating follow-up observations from complementary instruments, both in space and from the ground. This is possibly the most important of Hubble's advantages: by imaging celestial objects with unprecedented clarity, HST has forced astronomers to look at these objects and their physical properties with different eyes.



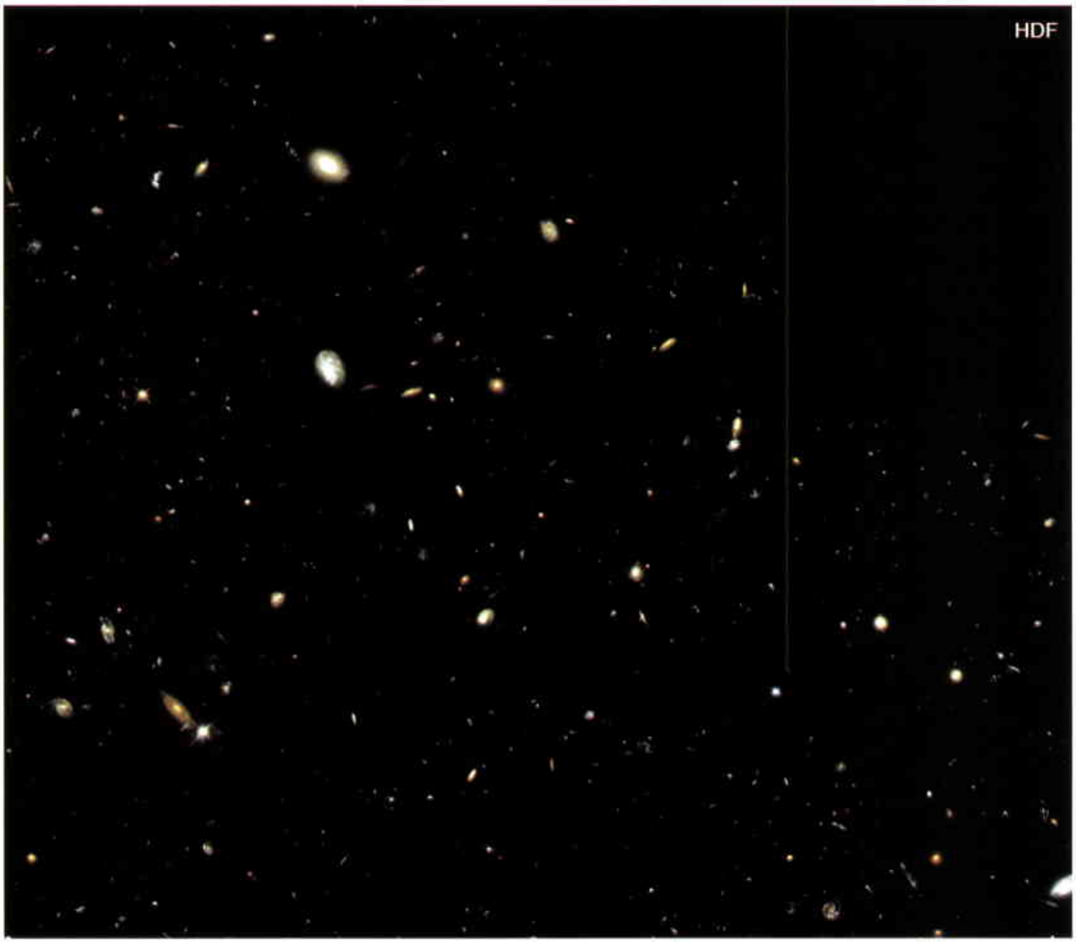
NGC 4038-9B

The Deep Fields

The project known as the 'Hubble Deep Fields' is the most striking example of HST driving other areas of astrophysics research. The Hubble Deep Fields are observations of small areas of the sky obtained by adding together about 350 individual exposures of the same field, with a total exposure time of more than 100 hours, compared with typical Hubble exposures of a few hours. Two Deep Fields, one in each of the Northern and Southern Hemispheres, were carefully selected to be in as empty a patch of sky as possible so that Hubble would look out far beyond the stars of our own Milky Way and out past nearby galaxies. In the case of the Deep Field South, the field also contained a quasar, which has been used as a cosmological light beacon to detect intergalactic clouds lying between the quasar and the observer.

The results were astonishing: almost 3000 galaxies were seen in each image. A statistical analysis of the angular distribution of the galaxies indicated that many of them belonged to a very young Universe, at a time when star

formation had just started. The Deep Fields were immediately used by large ground-based observatories, in particular by the 10 m Keck Telescope and more recently by the ESO Very Large Telescope, as a finding chart for follow-up spectroscopic observations. Indeed, it is only large collecting mirrors, 8–10 m in diameter, that can gather enough light to obtain a spectrum of these faintest galaxies and so determine their cosmological redshift. The problem for Earth-bound telescopes is to know where to point them, since the smearing by the Earth's atmosphere makes the images of the faintest galaxies almost indistinguishable from the background noise. The Hubble Deep Fields solved the problem by providing a highly accurate map of these objects, and here the synergy between space- and ground-based telescopes produced a giant step in our understanding of the history of the early Universe. Many of these galaxies showed the highest redshifts ever observed – more than 5 in some cases. Subsequent statistical analysis, based on these spectroscopic redshifts, allowed astronomers to obtain a relationship between the photometric colours of the galaxies and their redshifts. The resulting cosmological map indicates that remote galaxies are smaller and more irregular that those nearby, supporting the idea that galaxies form by the gravitational coalescence of smaller parts.



The age and size of the Universe

The top-ranked scientific justification for building Hubble was to determine the age and size of the Universe through observations of Cepheid variables in distant galaxies. Cepheids are a special type of variable star with very stable brightness variations. The period of these variations depends on physical properties of the stars such as their mass, age and therefore true brightness. By detecting Cepheid variables in a galaxy and measuring the period of their brightness variation, astronomers can effectively derive the distance of the parent galaxy. The high angular resolution of the HST cameras can distinguish individual stars in distant galaxies where a ground-based telescope, powerful though it may be, would see only a blurred patch of light. Advanced automated techniques for the detection of point-like objects were used to extract and compare the information obtained by Hubble at carefully planned time intervals, and a number of Cepheids were discovered and measured. This fundamental work, which is still in progress, is building a new solid rung on the cosmological distance ladder.

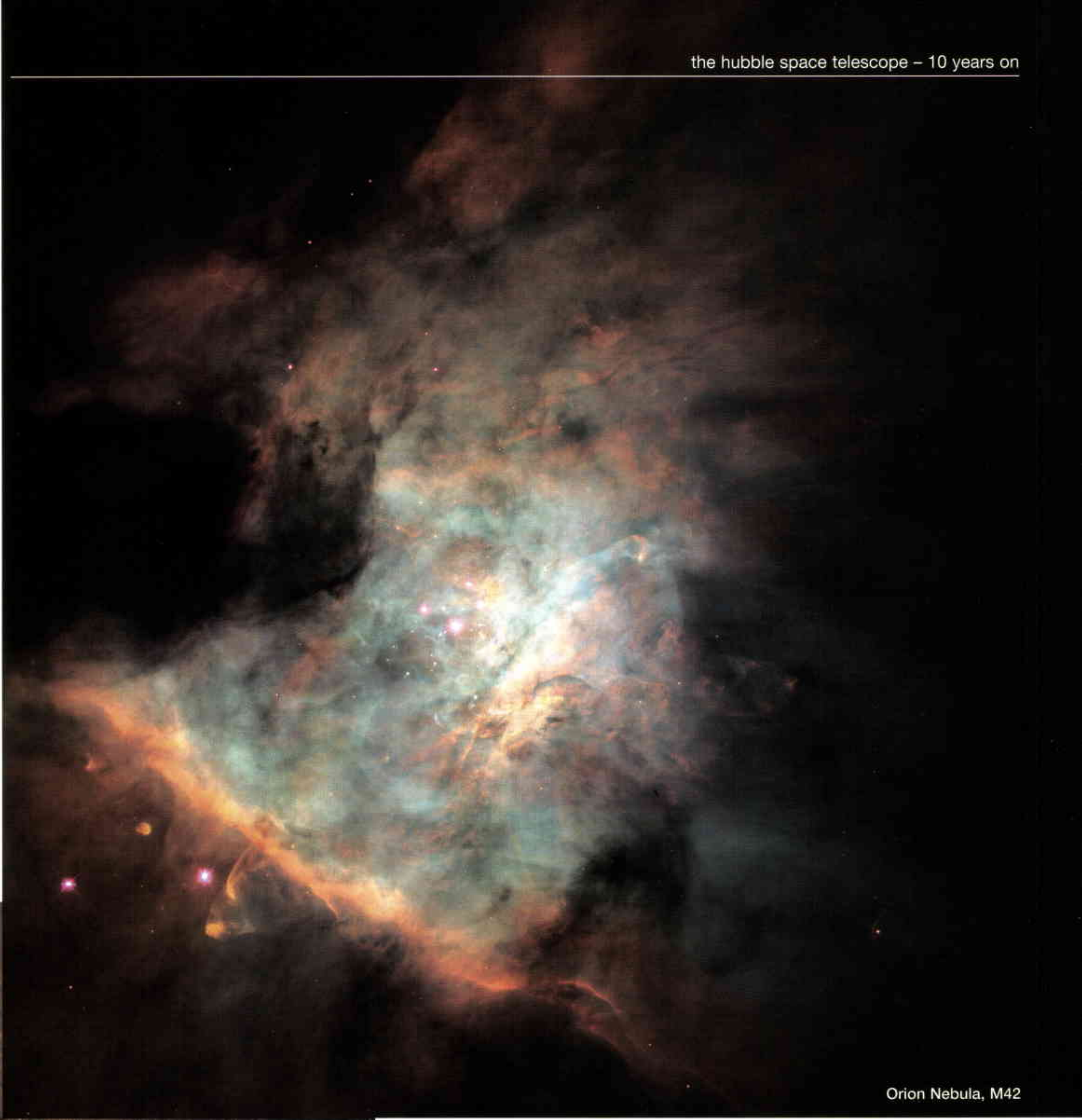
In the past, several of these galaxies for which Hubble has measured their distance using the Cepheid method, have hosted one or more supernovæ. A supernova is a massive star that, towards the end of its life, when it has exhausted most of the available fuel, explodes almost completely. During the outburst, the star brightens by a factor of a billion or more and up to 10^{51} ergs of energy are generated. For a given class of supernova, the maximum brightness reached during the explosion is believed to be almost constant, making them ideal extragalactic distance indicators. The new accurate Cepheid measurements of the distance of the host galaxies combined with the observational data from the supernovæ, provide an excellent tool for calibrating the absolute magnitude that these objects attain at their maximum brightness. These data not only improve the map of the Universe and of the expansion that the competing cosmological models have to account for, they are also preparing a toolbox that will be invaluable when new instruments, such as the Next-Generation Space Telescope, detect even more distant supernovæ.

The formation and evolution of stars

Hubble has also greatly improved our knowledge of stars in their different stages of evolution. The fields in which HST has excelled most are those requiring its high resolution or its sensitivity in the UV and IR wavelength ranges. For example, important progress has been made in the study of globular clusters, especially those in other galaxies. These objects are very densely populated and the stars are so packed together that only Hubble could observe them as distinct objects. HST was the first telescope to observe white dwarfs in globular clusters directly: white dwarfs are stellar remnants and provide a fossil record of their progenitor stars. Through these measurements, it is possible to estimate the age of these ancient clusters – an important test for any cosmological model.

The near-IR NICMOS combined camera and spectrograph was used to look through the dusty clouds that usually surround and hide the star-formation regions in our Galaxy. It was found that newborn stars are grouped into clusters and their environment is far from being a quiet one, crossed as it is by jets and shock waves.

On many occasions since its launch, Hubble has observed the site of the explosion of the Supernova 1987A in the Large Magellanic Cloud. Again, thanks to its very high resolution, it has been possible to monitor the progress of the cataclysmic explosion in detail. Images clearly show two rings of gas on each side of the exploding star that were expelled by the progenitor star several thousands of years before the final explosion. In recent years, astronomers have watched as different parts of



Orion Nebula, M42

these rings light up as they are hit by the expanding blast wave from the explosion. The expansion of the exploded material, which will eventually form a supernova remnant similar to that of the Crab Nebula, has also been monitored.

Some of the most impressive images obtained by Hubble are those of the star-forming regions in our Galaxy, such as the Orion and the Eagle Nebulæ. These images show in great detail the complex interaction between the radiation generated by the new-born stars and the molecules and dust of the cloud from which they were formed. It is clear now that the existing simplified models – for instance those that assume spherical symmetry and smooth matter density variations – are completely inadequate to describe the actual picture. Since chemical-abundance estimates in other galaxies are based on these models, it is now realised how important is to use the new detailed information on these H II regions to improve other predictive models. In the same H II regions, Hubble also detected dust discs, dubbed proplyds, around the newly-born stars. These discs may well be young proto-planetary systems in the early phases of their evolution.

Our Solar System

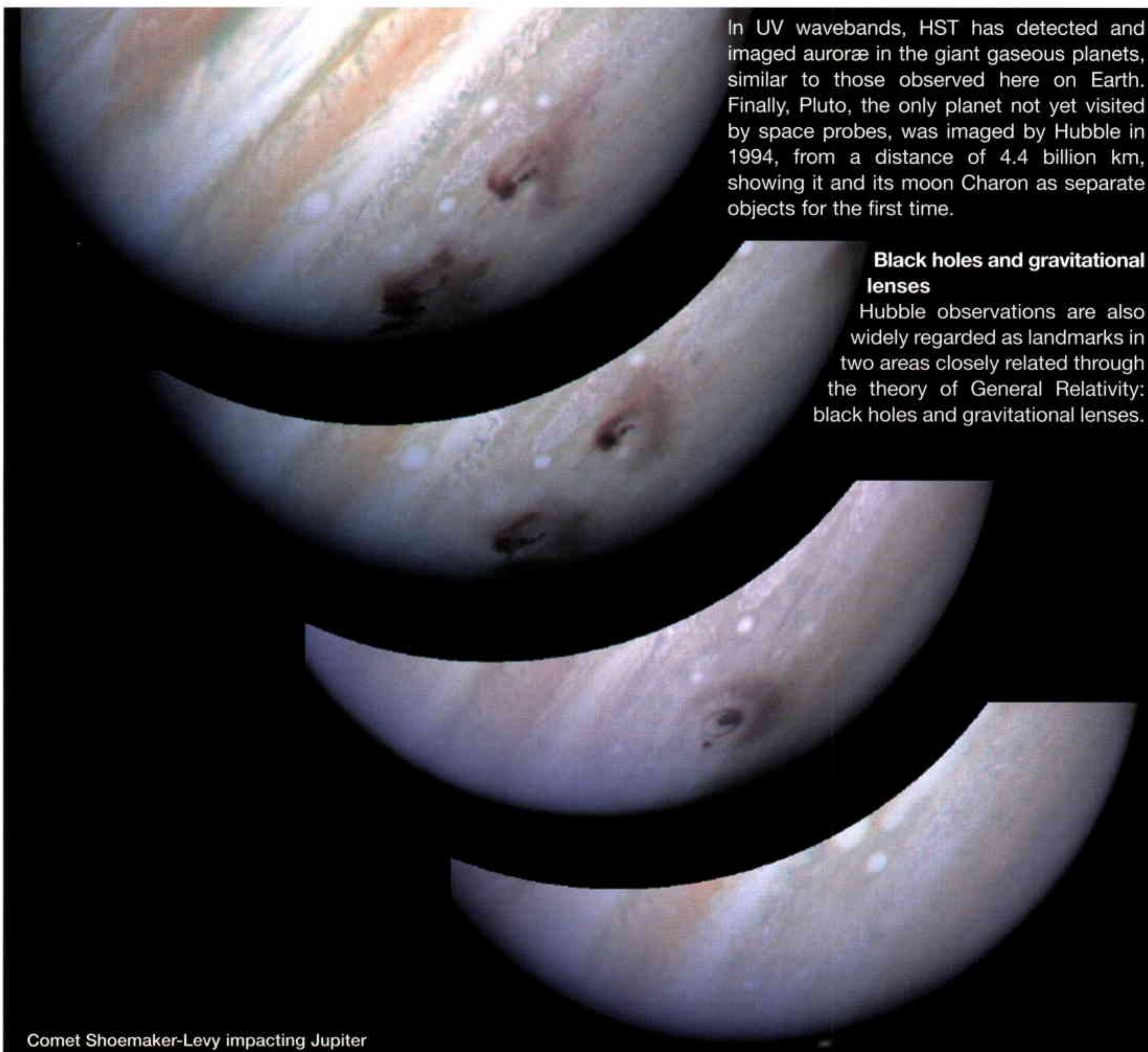
HST's high-resolution images of the planets and moons in our Solar System can only be surpassed by pictures taken from spacecraft that actually fly by the planets. However, Hubble has the big advantage that it can return to look at these objects periodically and so observe them over much longer periods than any passing probe. Regular monitoring of planetary surfaces is vital to the study of planetary atmospheres and geology, where evolving patterns such as dust storms can reveal much about the underlying processes. Hubble can also observe phenomena such as volcanic eruptions directly. The asteroid Vesta is only 500 km in diameter, but has been surveyed by Hubble from a distance of 250 million km. The resulting map of its surface shows many lava flows, dominated by a huge impact crater.

Hubble is also able to react quickly to sudden events occurring in the Solar System. In 1994 it followed fragments of Comet Shoemaker-Levy on their last journey to Jupiter and delivered stunning high-resolution images of the impact scars and of their temporal evolution, from which much new information on conditions in the Jovian atmosphere could be deduced.

In UV wavebands, HST has detected and imaged auroræ in the giant gaseous planets, similar to those observed here on Earth. Finally, Pluto, the only planet not yet visited by space probes, was imaged by Hubble in 1994, from a distance of 4.4 billion km, showing it and its moon Charon as separate objects for the first time.

Black holes and gravitational lenses

Hubble observations are also widely regarded as landmarks in two areas closely related through the theory of General Relativity: black holes and gravitational lenses.



Comet Shoemaker-Levy impacting Jupiter

In the 1950s and 1960s astronomers found objects, such as quasars and radio sources, whose energy output was so immense that it could not be explained by traditional sources of energy such as that produced by normal stars. It was suggested that their energy output could best be explained if massive black holes were at the centres of these objects.

Before Hubble was launched, a handful of black-hole candidates had been studied, but the limitations of ground-based observations were such that irrefutable evidence for their existence could not be obtained. Black holes themselves, by definition, cannot be observed directly, but their presence can be inferred from their effects on their close surroundings. These include powerful jets of electrons that travel many thousands of light years from the centres of the galaxies, and matter that falls towards the black hole with an increasing spiralling speed. Accurate measurements of this infall velocity, once again made possible only by the high resolution of Hubble, allow the mass of the black hole itself to be determined. In some galaxies, Hubble found black holes as massive as 3 billion solar masses.

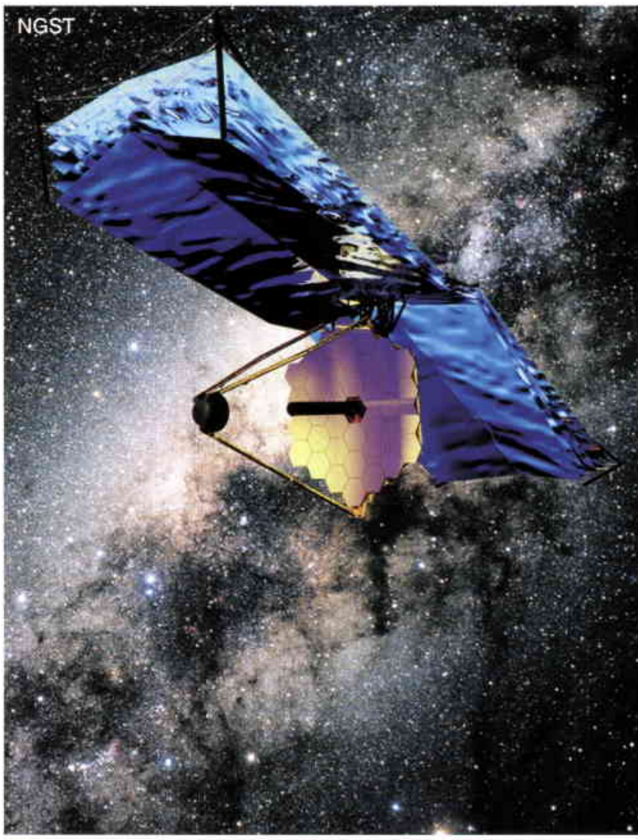
While this might have been expected, Hubble has also provided the strong and unexpected evidence that black holes may exist in the centre of all galaxies. Furthermore, it appears that larger galaxies harbour larger black holes. There must be some mechanism that links the formation of the galaxy to that of its black hole and vice versa – an observation that has profound implications in the theory of the formation and evolution of galaxies.

The bending of light by gravity was the first experimental proof of the validity of the Theory of General Relativity. The effect is very small and, before Hubble, only a few gravitational lens candidates were known. Taking advantage of its sensitivity and resolution, Hubble has now demonstrated how large massive clusters of galaxies can act as powerful cosmic telescopes, imaging distant galaxies and quasars that lie beyond the clusters as characteristically distorted multiple arcs. The importance of these cosmic mirages is that, from the detailed measurements of the distorted arcs, the total mass of the cluster can be derived, regardless of whether the mass is luminous, as are stars, or dark, as is dust, diffuse gas or even exotic massive particles. These mass estimates, directly derived from a gravitational effect, have profound implications for cosmological models. The proven possibility of measuring these gravitational distortions on a large scale, albeit in a statistical sense, has stimulated a new and important research line for which an significant fraction of observing time, both with Hubble and with large ground-based telescopes, is being invested.

The future

Hubble is now half-way through its operational lifetime. Its observations have opened up many vigorous research lines, setting the scene for more ambitious projects. While Hubble will continue to operate in a similar manner through its second decade, with improved capabilities as new instruments are installed, a change in its scientific use can be expected. The huge success of the Deep Fields experiment, in which a large amount of observing time was allocated to a single well-focussed programme, has already modified the HST time-allocation policy. Astronomers are now encouraged to propose large, survey-type observing programmes which, as the Deep Fields experience shows, provide a precious mine of uniform data, out of which hundreds of research groups can extract different scientific aspects, and complementary observations with other space and ground-based observatories can be planned.

Hubble has also paved the way for its natural successor, the Next-Generation Space Telescope (NGST). Hubble's ability to map the distant Universe ends abruptly when the light of the most distant galaxies, heavily redshifted by the cosmic expansion, falls beyond the wavelength range that Hubble can observe. In order to observe the galaxies in their making and light from the first stars in the Universe, it is necessary to observe further out into the infrared region. This is one of the main reasons why NGST has been selected as an IR telescope with a large collecting area. The observatory will be effectively protected against the radiation from Sun and Earth, to allow instruments to cool down and operate at about 40 K. NGST is currently being studied by NASA, ESA and CSA (Canadian Space Agency) for a possible launch around 2010.



The XMM-Newton Observatory – A Year of Exciting Science

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The XMM-Newton space observatory – a Cornerstone mission in ESA's Horizon 2000 Programme and originally referred to as the High-Throughput X-ray Spectroscopy Mission – was placed into a 48-hour orbit by the first commercial Ariane-5 launch (V504) on 10 December 1999. This brief survey of the scientific results obtained during the first year of XMM-Newton operations clearly illustrates that the observatory is more than living up to expectations and already providing unique and promising results, even before full scientific data analysis gets officially underway.

Introduction

Following an original mission proposal made to the Agency in 1982, the primary objectives for XMM-Newton were initially discussed by the scientific community at an ESA-organised workshop in Lyngby, Denmark, in June 1985. High-quality X-ray spectroscopy of faint sources was identified as the next major step following a series of X-ray missions flown in the 1990s. Spectroscopy is one of the key tools for the scientific interpretation of astronomical data, involving the separation of X-ray 'light' in such a way that the composition, temperature and density of the extremely hot gases in the Universe can be studied under a variety of circumstances.

Previous observatories have detected X-ray emission from a large variety of celestial sources, including halos of gas around massive galaxies, nuclei of 'active' galaxies, accretion disks around compact objects (like black holes, neutron stars), stellar coronae and supernovae remnants. Until now, high-resolution spectroscopy has played a modest role in X-ray astronomy due to a lack of sophisticated instruments and to a paucity of X-ray photons: one needs large collecting areas to capture them at a sufficient rate. The X-ray collecting power of previous observatories was largely inadequate for such detailed analysis.

XMM-Newton was designed to provide a major step forward by addressing these deficiencies: high-quality spectral measurements require powerful telescopes with the highest possible collecting area. ESA therefore established a design consisting of three multi-mirror grazing-incidence telescopes, and a payload complement including three European Photon Imaging Cameras (EPIC, Principal Investigator: M.Turner, Leicester University, UK) and two Reflection Grating Spectrometers (RGS, PI: A. Brinkman, SRON, Utrecht, The Netherlands), together with an Optical Monitor (OM, PI: K. Mason, MSSL, Dorking, UK) for complementary observations at optical wavelengths.

The payload

The overall layout of the instrument package on the XMM-Newton observatory is shown in Figure 1. At the left-hand end are three large cylindrical structures, which are the mirror modules. Two of these are shown with the RGS grating at their exit. The detectors are located at the right-hand end of the spacecraft. The green horns are the cooling radiators behind the EPIC MOS cameras. The red and pink plates are the radiators behind the RGS and EPIC PN detectors, respectively. The OM is located on the mirror platform.

Mirrors

One of the major features of the XMM-Newton observatory is its ability to make X-ray images of the sky. This is achieved by reflecting X-rays off metallic mirrors under grazing-incidence conditions. In order to deliver a high throughput of X-ray photons, each of the three XMM-Newton telescopes consists of 58 quasi-conical mirrors. X-rays are reflected on their inner gold-coated surfaces. The large collecting effective area of the telescopes is achieved by nesting the 58 mirrors in a confocal configuration and thereby filling their entrance aperture as much as possible. This design requires the production of a large quantity of thin mirrors with ultra-smooth reflecting surfaces. A replication technique involving the electro-forming of nickel mirrors from super-polished mandrels was selected (see ESA Bulletin No. 100). This technique was pioneered for the ESA mission Exosat (1983–1986).

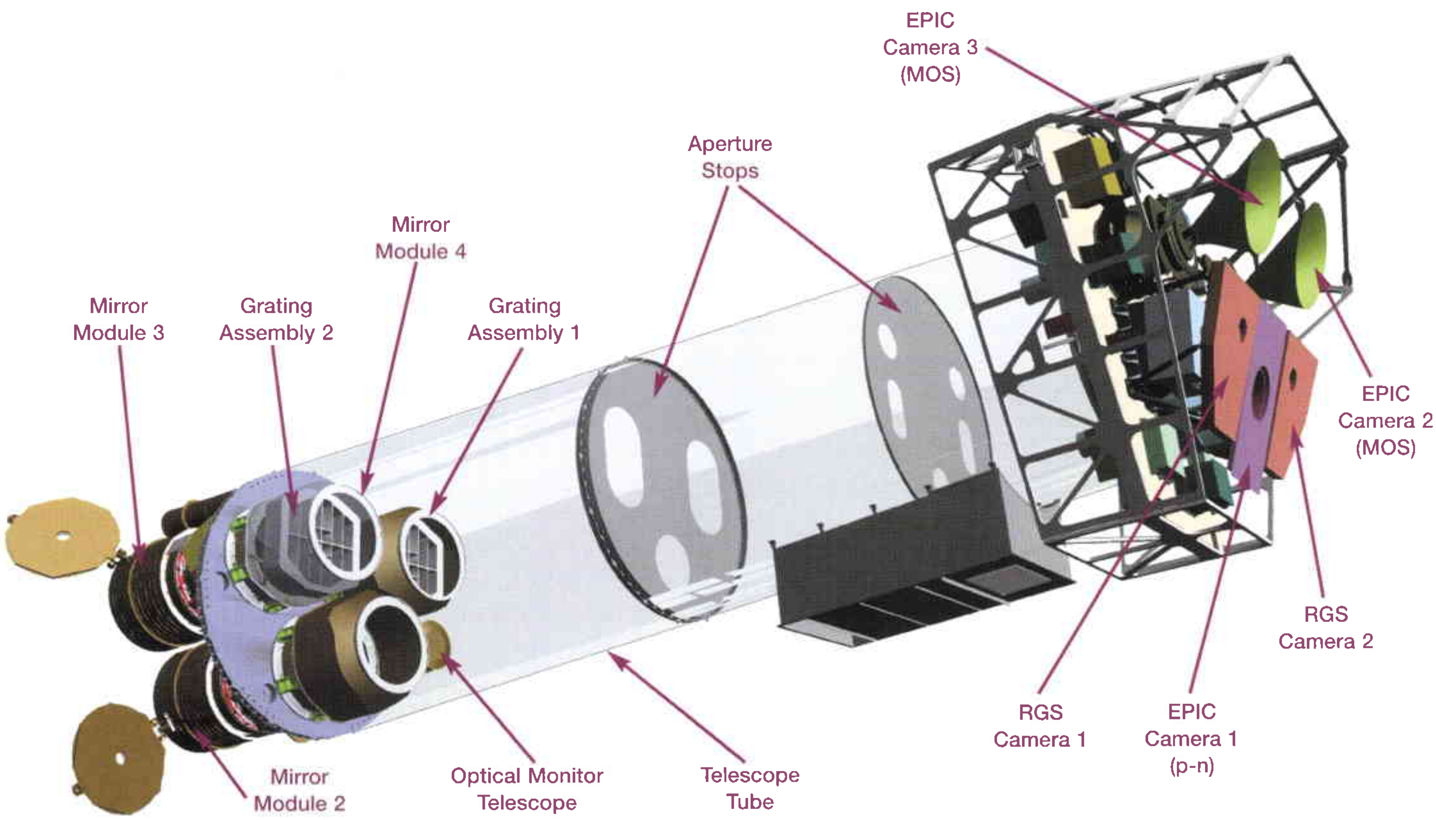


Figure 1. Exploded view of the XMM-Newton spacecraft

XMM-Newton's three X-ray telescopes and the associated instruments, RGS and EPIC, as well as the Optical Monitor, are operated simultaneously and directed at the same point on the sky, thus providing optimum coverage of each target using this complementary suite of instruments.

EPIC

Located at the focal plane of each of the XMM-Newton mirror assemblies is an EPIC (European Photon Imaging Camera) detector. These each employ several charge-coupled-device (CCD) sensors to record the position and energy of each X-ray photon that is detected. Two of the EPIC cameras employ MOS (metal-oxide-semiconductor) technology CCDs, which have been specially developed from a more conventional TV-camera sensor. The third EPIC camera uses a more novel PN CCD technology, which is fabricated from a single wafer of silicon. Both CCD camera types are operated at a temperature of -100°C. This is achieved through the use of a passive radiator cooling plate, which effectively uses deep space to cool the instruments. The cameras are equipped with filters to block visible light from reaching the detector. The EPIC instruments operate in the 0.2–10 keV range and, in combination with the XMM-Newton mirror assemblies, they provide the largest X-ray imaging collecting area ever.

RGS

Two of the three X-ray telescopes consist of a combination of a mirror assembly and a reflection-grating assembly used by the RGS experiment (the greyish grid-like units in two of the three modules to the left in Fig. 1). The reflection gratings behave like a prism with visible light, and reflect X-ray photons with an angle that depends on their wavelength (energy). The diffracted photons are collected by a strip of 9 CCD detectors at a position that provides a measurement of their wavelength. Part of the beam exiting the X-ray telescopes passes through the stack of gratings without being intercepted. These photons are imaged on the MOS-detectors in the EPIC cameras located at the prime foci of each of the X-ray telescopes.

The Reflection Grating Spectrometer (RGS) is a dispersive spectrometer that, for the first time in X-ray astronomy, uses reflection gratings as dispersive elements. The instrument provides high spectral resolving power over the wavelength band from 0.33 to 2.5 keV, an energy range that contains the major characteristic emission lines of the most abundant heavy elements. The instrument permits measurements of relative intensity for different emission lines of the same species, and thus allows the temperatures, densities and chemical abundances in hot gas to be measured.

OM

The Optical Monitor (OM) is an instrument with a primary mirror of 30 cm diameter, based on a modified Ritchey-Chrétien design. Because of the low sky background in space, the sensitivity of the OM, using a relatively small mirror, is comparable to that of a 4-m telescope at the Earth's surface. The OM operates in the blue part of the optical spectrum and in the ultraviolet (160–600 nm). Its ultraviolet (UV) sensitivity adds a unique and valuable feature to the XMM-Newton mission, because UV light is not accessible from the ground as it is absorbed by the Earth's atmosphere. The value of having simultaneous optical coverage with the X-ray instruments was a lesson learnt from Exosat.

The OM instrument is co-aligned with the X-ray instruments, but only covers the central 17x17 $arcmin^2$ of the 30 by 30 $arcmin^2$ field-of-view of the X-ray imaging cameras (EPIC). The incident light is focussed by the primary and secondary mirrors onto one of two redundant detector chains. Each detector chain consists of a filter wheel, a photon counting detector (multi-channel-plate intensified CCD) and its processing electronics. The OM filter wheel is equipped with different filters to select specific portions of the visible or ultraviolet colours of interest. In addition, the wheel is equipped with 'grisms' – dispersive elements very much like a high-quality prism. These decompose the light from a source to allow detailed study of its spectrum. Where the filters in the EPIC instrument are intended to reject visible light, the filters in the OM instrument are used to look at different wavelength bands. These filters are designed such that an easy comparison with ground-based measurements (using similar filter arrangements) can be made. Their effect in terms of a changing view of the sky in the different filters is illustrated in Figure 2.

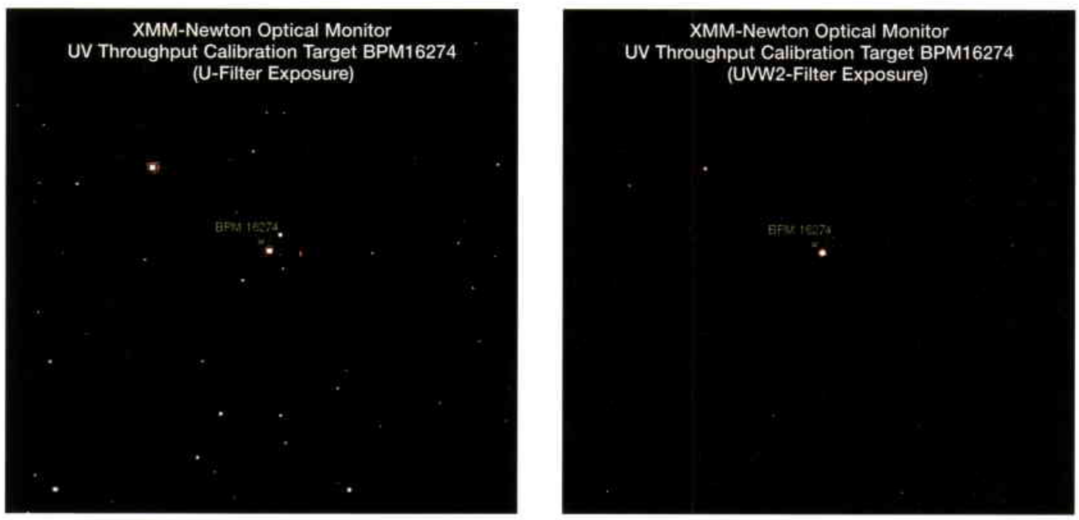


Figure 2. OM image of the field centred on the white dwarf BPM16274 in the visible (left) and in the ultraviolet (right). Objects that are relatively bright in the UV are rare, allowing ready identification

Calibration

After the initial in-orbit activation and commissioning activities, the first scientific operations involved extensive and accurate calibration of the payload. Calibrating instruments like those on XMM-Newton involves observing a well-known object and checking to see if the response of the instruments matches that predicted on the basis of its known performance on the ground, and the characteristics of the astronomical object. Until this is completed, and the instrument's performance is fully understood, astronomers cannot be sure that the data they receive correctly interprets the brightness or positions of any objects. For XMM-Newton, these in-orbit measurements lasted some three months.

One of the major activities in calibrating the mirror modules on XMM-Newton is to establish the precise imaging performance in terms of sharpness and throughput. As part of this exercise, the satellite observed the open stellar cluster NGC 2516. Figure 3 shows an EPIC-MOS observation of this object, where more than a hundred stars were detected. The figure shows that the sources are, on average, brighter close to the centre of the field of view. This artefact results from a vignetting effect caused by the X-ray telescopes. Also, the images of individual stars vary significantly over the field of view due to geometrical off-axis aberrations induced by the grazing-incidence optics. These instrumental effects need to be corrected when building a true, corrected image of the sky. In-orbit calibration activities also included the precise determination of the pointing of the instruments relative to one other, and the characterisation of the telescope imaging properties and effective collecting area.

The calibration of the Reflection Grating Spectrometer (RGS) was centred on the determination of the energy scale, which depends on the exact alignment of all individual units in the light path of the X-ray photons (mirror, grating and camera). This could not be determined to final accuracy on the ground because the high quality of the mirrors required a test facility in which the X-ray source is more than 500 m away from the detectors. An illustration of how such a calibration can be performed is shown in Figure 4.

After completion of the alignment of the RGS instrument, and consequently the energy-scale calibration, the detection efficiency (effective area) and the detailed response of the instrument to individual emission lines were calibrated. Figure 2 illustrates part of the calibration of the optical monitor. The images show the field of the calibration target BPM16274 at different wavelengths. The number of sources visible in the UV image centred around 190 nm is significantly reduced compared to the number seen at visible wavelengths around 370 nm. The target BPM16274, a white dwarf, in the centre of the image remains as one of the few sources also visible at UV wavelengths. Because this is a source with known, stable properties, it is one of those used to calibrate OM performance.

Scientific results

The XMM-Newton observatory is open to the astronomical community at large for observations. This is achieved through an Announcement of Opportunity (AO), also known as a 'Call for Observing Proposals'. This process for XMM-Newton took place in the summer of 1999, and the best observing proposals were selected through peer review. Another component of the early observing programme for XMM-Newton is the performance verification phase, which consists of a series of observations dedicated to proving that the XMM-Newton observatory can actually achieve what was originally discussed at the 1985 Lyngby workshop. The current XMM-Newton observing programme thus consists of:

- calibration observations
- performance-verification observations
- guaranteed-time observations
- open-time (AO) observations
- targets of opportunity.

Targets of opportunity are observations for which dedicated time is allocated by the Project Scientist, and can be scheduled on a very short time scale. They allow for 'instantaneous' observations of the more interesting transient astrophysical phenomena. Many of the recent observations are currently being analysed in detail, and the following sections provide a preview of what are clearly exciting prospects for X-ray astronomy

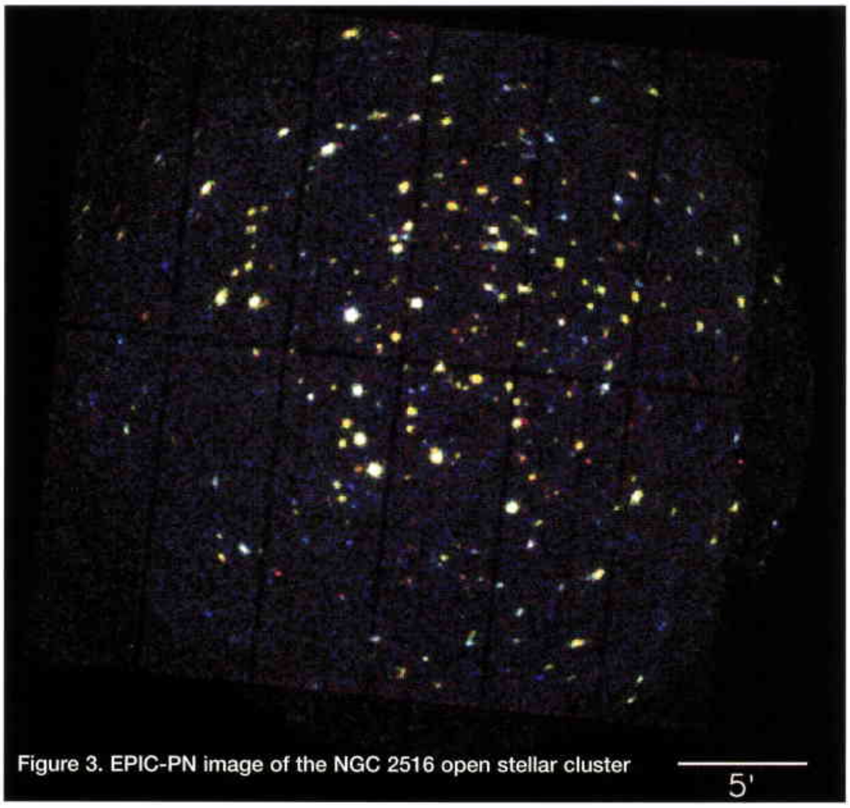
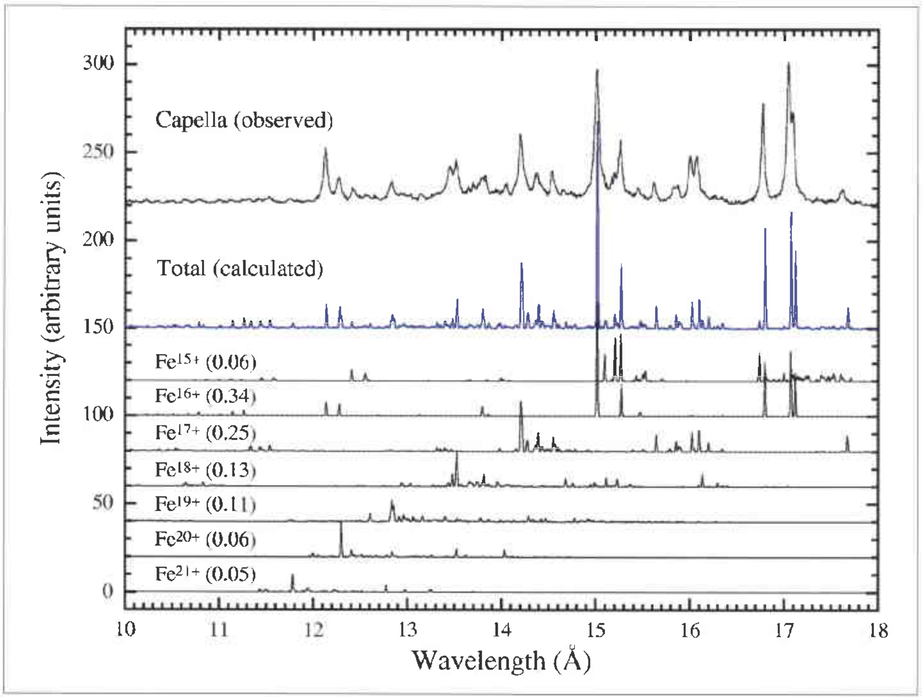


Figure 3. EPIC-PN image of the NGC 2516 open stellar cluster

Clusters of galaxies

Clusters of galaxies are among the largest structures in the Universe, consisting of hundreds of galaxies bound together by their mutual gravitational attraction. They are of great interest for cosmologists as indicators of how the early Universe evolved, when the initially smoothly distributed matter started to clump together and form the structures that we can now observe in detail in X-rays. Visible-light images of a cluster of galaxies show the galaxies themselves, but not the hot gas that often lies between them. In contrast, an X-ray

Figure. 4. Observed RGS spectrum of Capella (top). The blue line displays the sum of the individual contributions of several species of highly ionised Fe. The energies of the related emission lines are accurately known from ground measurements in Tokamak plasmas. These known emission lines can be used to fit the measured spectrum using the RGS internal alignment as the adjustable component



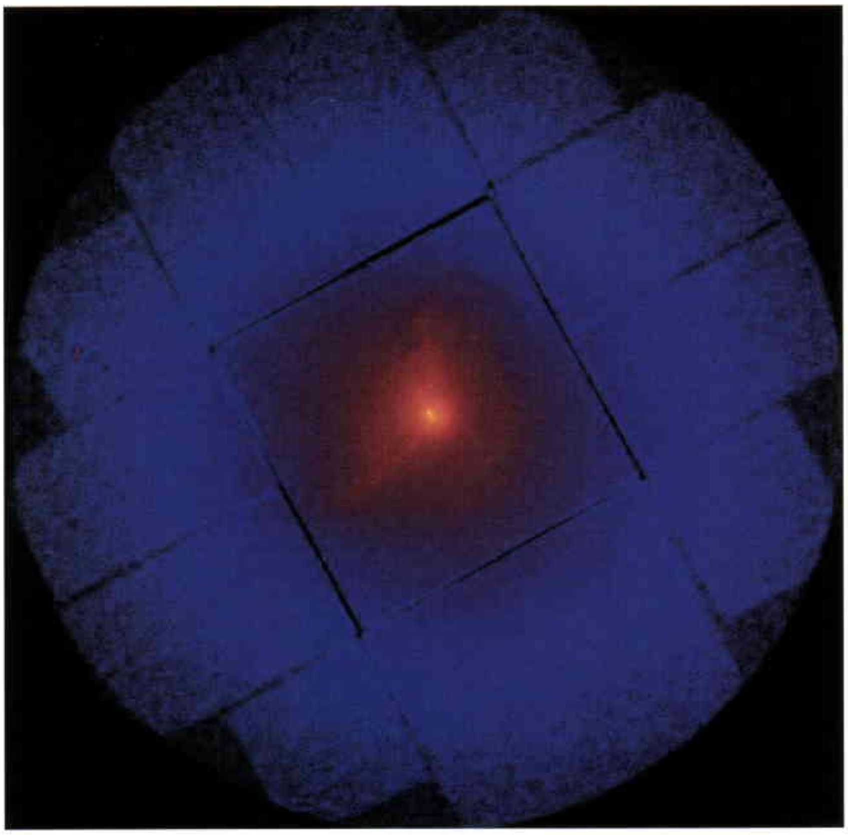


Figure 5. EPIC-MOS image of M87 in the Virgo cluster of galaxies

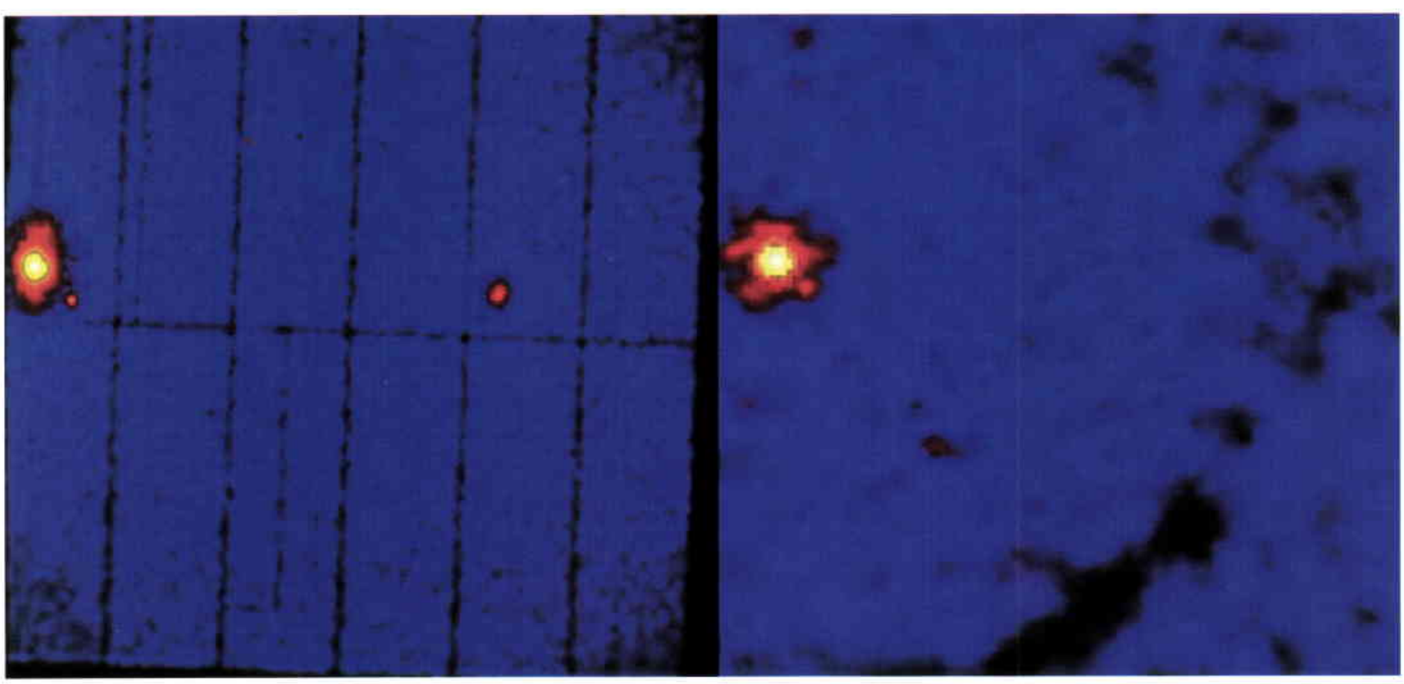
Figure 6. On the left is an EPIC PN image of a serendipitously discovered cluster of galaxies (red patch to right of centre) in the field of a Milky Way supernova remnant (left part of image). On the right is a Rosat low-energy X-ray picture of the same field

image mainly shows these hot gases, which at millions of degrees shine brightly in X-rays, and some of the constituent galaxies appear more faintly.

In Figure 5, we see the EPIC camera image of a part of the relatively nearby Virgo cluster. The picture is centred on the bright galaxy M87, which appears as two bright points (actually the very core of the galaxy and a previously known 'jet' of high-energy particles streaming away from the centre). The hot gas of the cluster surrounding M87 is seen as extended diffuse light. This exhibits some structure due to shocks and violent motions in the gas. This is caused by galaxies moving through such clusters with very high velocities, up to hundreds of kilometres per second. Finally, towards the outer edge at the left side of this image, a small red object is seen which is the emission of an individual galaxy standing out against the hot gas.

During calibration observations of a region of the Milky Way, in one of the images taken by the EPIC X-ray cameras, a new object was discovered, an impressive X-ray source of unexpected brightness (to the right in Fig. 6). The target of interest had been the bright supernova in the left of the picture. Previous pictures of this region taken by the Rosat observatory had shown nothing similar. In the energy range observed by Rosat, low-energy X-rays from most objects have been absorbed by all of the gas and dust in the Milky Way. Inspection of the X-ray emission spectrum of the newly discovered source (Fig. 7) clearly identifies it as an extragalactic source, as the Fe emission line is clearly red-shifted from the energy that it would have had if it had been a local (i.e. Milky Way) source. Such red shifts, caused by the velocity with which the source is moving away from the Milky Way, can be used to determine the distance of the source as a fraction of the total size of the Universe. The extent of the source, combined with its red shift, indicates that this is indeed a cluster of galaxies.

This case clearly illustrates how the 'grasp' of the XMM-Newton observatory, especially at the higher energy X-ray end, allows for many new discoveries to be made.



Supernova remnants

At the end of their life span, many stars detonate in violent explosions known as supernovae. Such cataclysmic events were recorded throughout history because they drastically changed the night sky, and were sometimes even visible during daytime. From Chinese and Arabic records it is known that in May 1006 a new star appeared which was probably visible for three months, even during daylight.

Supernova explosions are the most energetic stellar events known. Despite their huge brightnesses soon after explosion, most of their energy appears as motion of matter. The outer layers of the star are ejected into space with an initial velocity of the order of 10 000 km/sec. The explosion expands as a blast wave and at some stage it will sweep up sufficient interstellar matter to start emitting copious amounts of X-rays.

One of the most powerful analysis tools for these objects is study of their morphology in the individual characteristic emission lines (Fig. 8). The collecting power of XMM-Newton allows for such detailed analysis of a wide variety of supernova remnants.

Figure 9 shows a raw EPIC-MOS image of the supernova remnant E0102-70 (bottom left) located in the Small Magellanic Cloud. The angular diameter of this remnant resulting from the explosion of a massive star about 1000 years ago is 40 arcsec (about 1/50th the diameter of the full Moon). This has to be compared with the on-axis point response of the XMM-Newton telescopes at low energy, which exhibit narrow cores just a few arcseconds wide, but have broad wings extending over more than 60 arcsec which are typical of X-ray grazing-incidence optics. The E0102-70 raw image was corrected for the telescope response using a deconvolution technique for the restoration of blurred images. The deconvolved image (Fig. 9, bottom right) reveals that the X-ray emission from the multimillion-degree shocked material is concentrated in a thick ring with sharp edges. The deconvolved image also shows bright blobs, indicating that the ejecta material pushing into the interstellar gas is breaking into clumps, dispersing heavy elements into space.

Figure 9 (top) shows another example of a raw (left) and deconvolved (right) EPIC-MOS image of a supernovae remnant, N132D. This remnant also results from the explosion of a massive progenitor star. Its diameter is about 80 arcsec, and its estimated age of 1300 years is similar to that of E0102-70. However, the

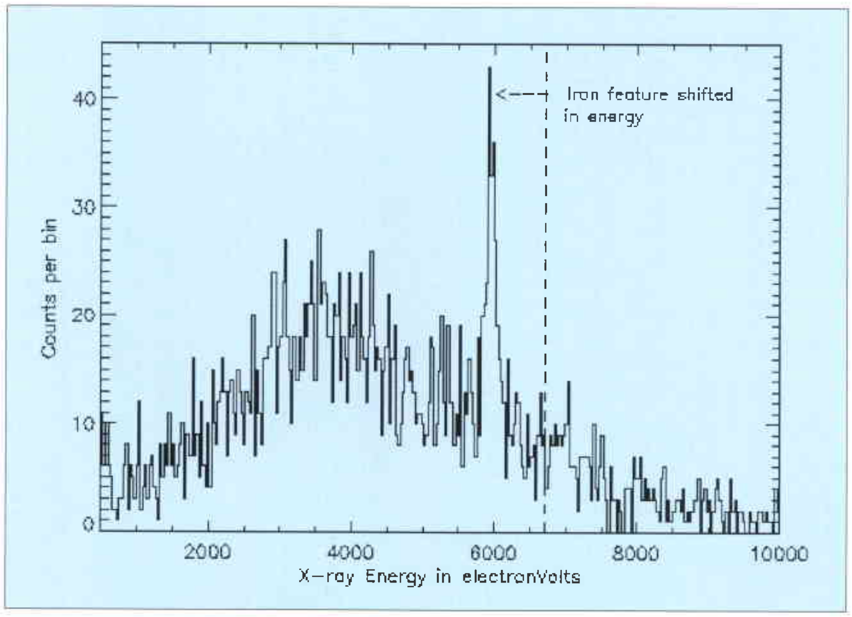


Figure 7. X-ray spectrum of the cluster of galaxies in Figure 6. The vertical dashed line represents the energy where the iron line feature would occur if not red-shifted

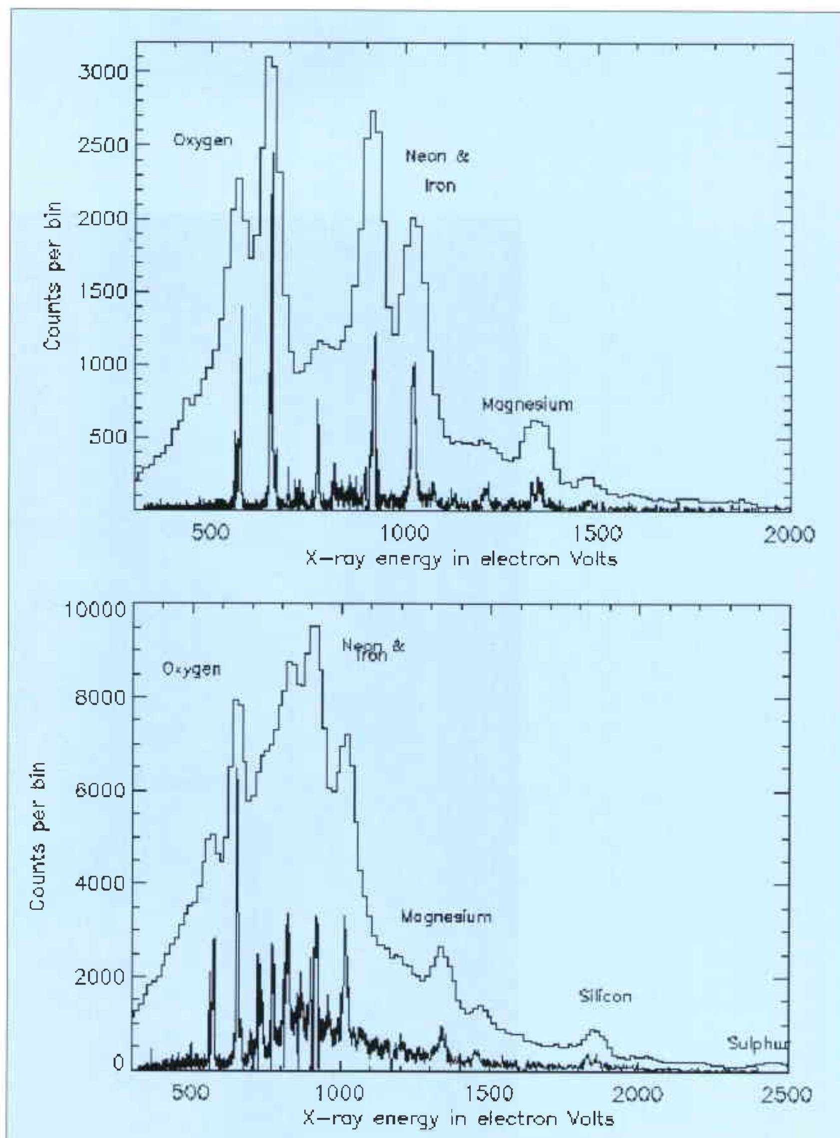


Figure 8. X-ray spectra of supernova remnants 1ES0102 (top) and N132D (bottom), with the RGS and EPIC spectra overlaid and the characteristic emission lines and their originating species indicated

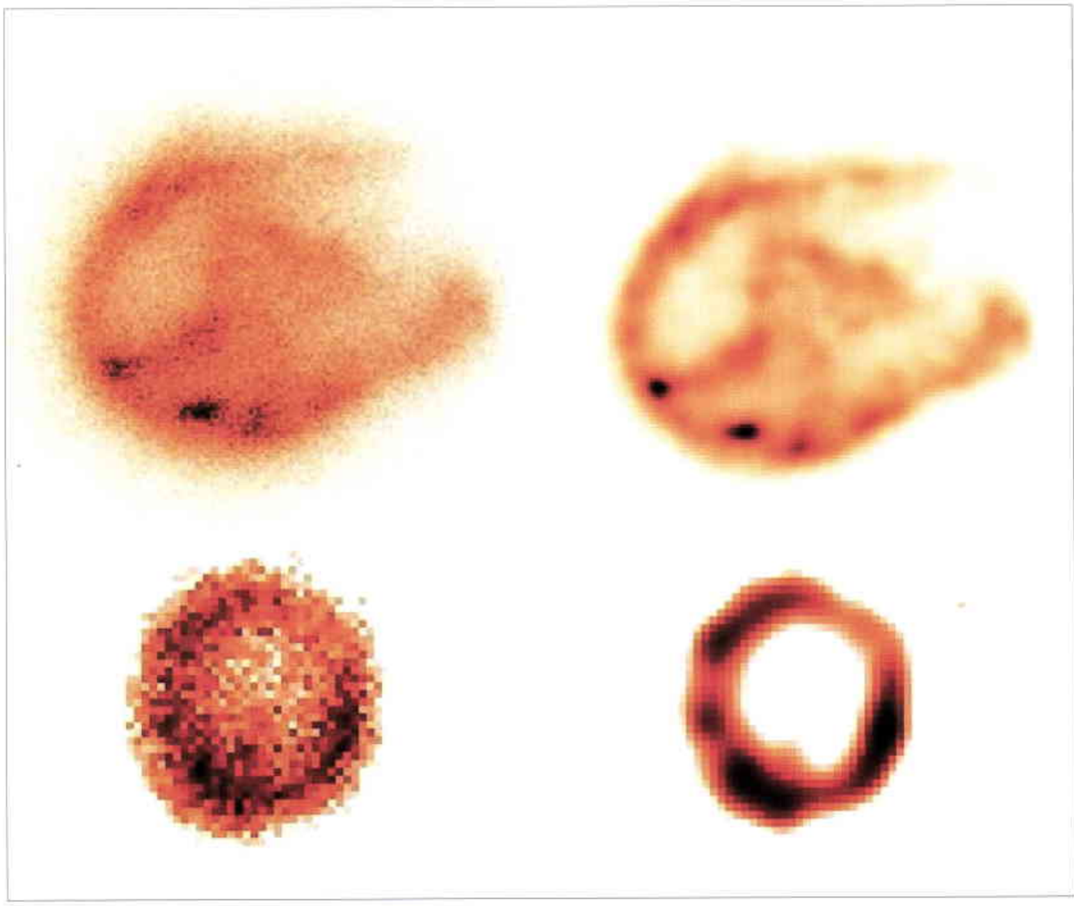


Figure 9. EPIC images of SNRs E0102-70 (bottom) and N132D (top) before (left) and after (right) deconvolution with the X-ray telescope point response

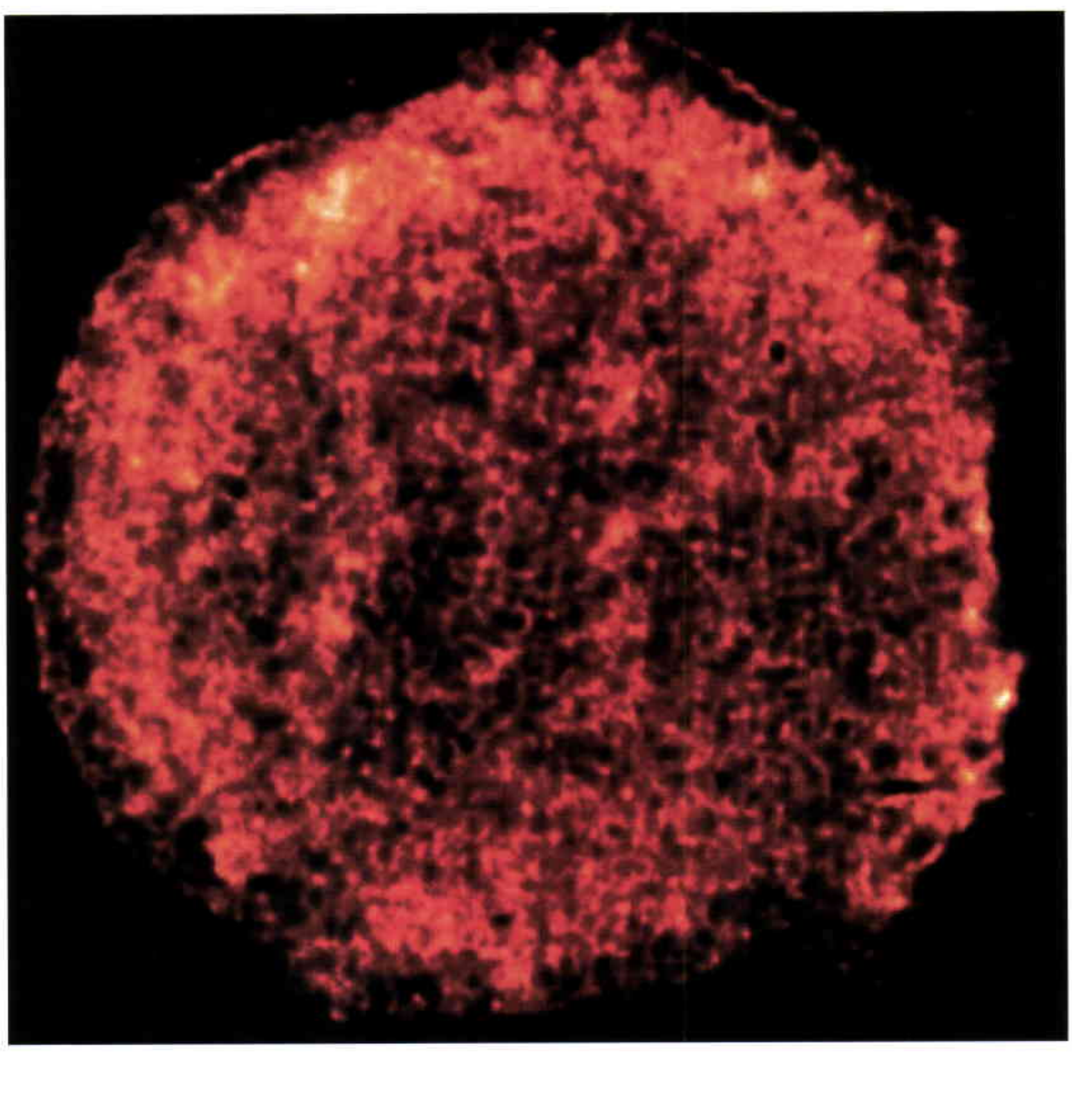


Figure 10. EPIC-MOS image of the Tycho SNR

deconvolved image of N132D reveals a more complex spatial structure. An outer shell with sharp edges is visible, but an extended region of diffuse emission with filament structures is also present. These two examples illustrate the ability of XMM-Newton's telescopes to study extended objects in X-rays with an accuracy comparable to that of ground-based optical telescopes, even at so remote a location as our neighbouring galaxies.

The EPIC and RGS data show further differences between these two supernova remnants in terms of their temperatures and chemical abundances. Figure 8 compares the X-ray spectra, clearly showing differences in intensity of the different emission lines from chemical elements. The RGS spectra reveal far sharper features, which are necessary for the most detailed analysis, but these are averaged over the whole remnant and so do not allow spectral studies on a small spatial scale. The EPIC data provide less detailed spectral information, but can be spatially resolved. This uniquely powerful combination of instruments gives a completely new view of, and a wealth of physical diagnostics for the conditions following such cataclysmic events.

Figure 10 shows the image of the Tycho supernova remnant obtained with the EPIC camera. This is a remnant of the stellar explosion witnessed by Danish astronomer Tycho Brahe in the 16th century. The majority of the chemical elements that make up planets, and support life itself (carbon, nitrogen, oxygen, etc.), were created in such events. Because details of how these explosions occurred, and how the elements may have been mixed up, remain unclear, astronomers expect new X-ray data to shed more light on the problem.

With EPIC's unique combination of spatial and spectral resolving power, it is possible to extract information from each chemical element in turn. As an indication, successive images made in the light of different chemical elements are shown. This shows that the locations of maximum intensity differ slightly for different chemical elements; this closely relates to the pre-supernova environment as well as the geometry of the original explosion (Fig. 11).

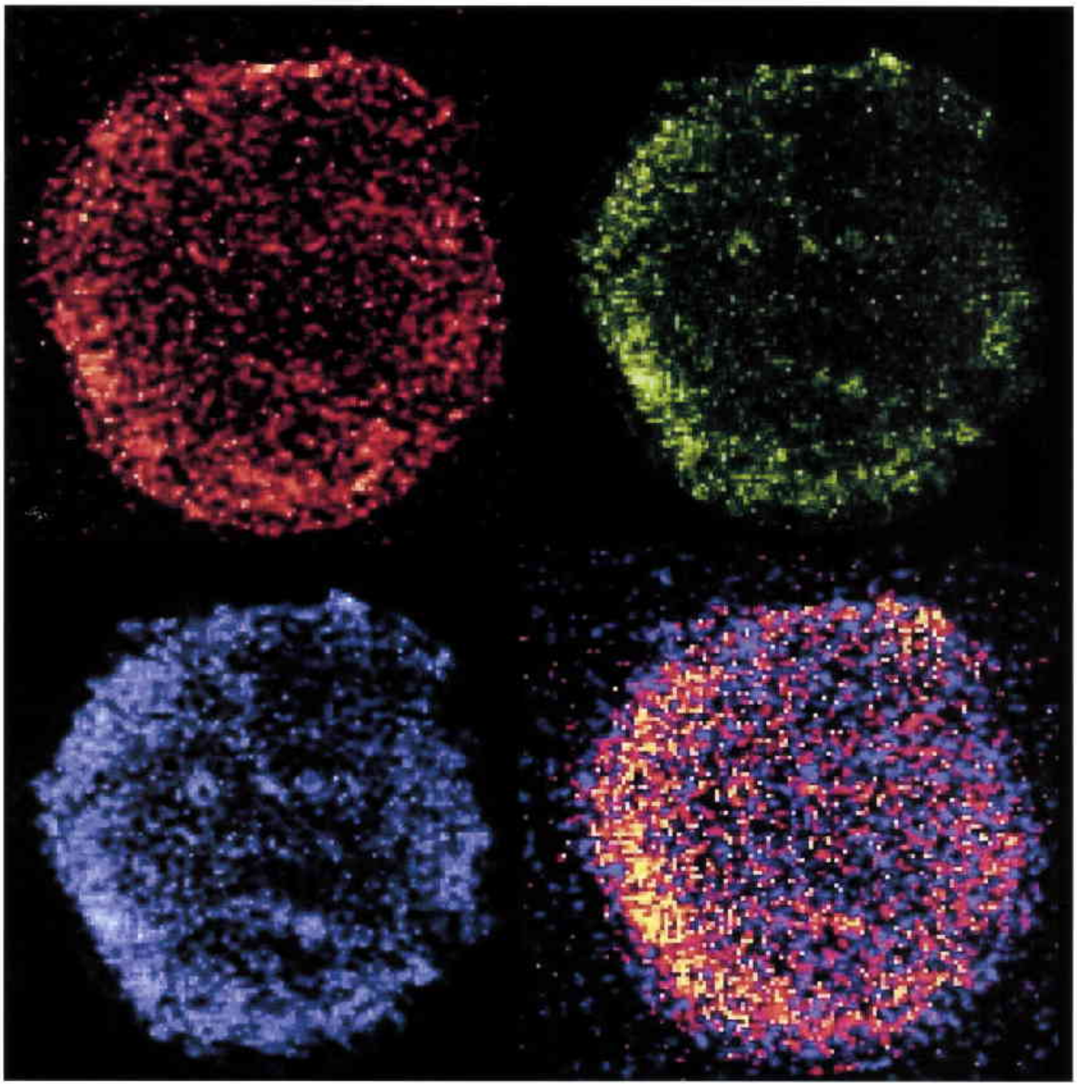


Figure 11. EPIC images of the Tycho SNR in calcium (red), sulphur (green), silicon (blue) and iron (yellow) emission lines. Careful inspection shows that the images are brighter in different locations

Deep surveys and the Lockman Hole

The very first observations in X-ray astronomy, made 40 years ago, revealed that the sky 'glows' with a uniform faint emission. Progressively more detailed studies have shown that most of this background glow is actually the superposition of the flux of many so-called 'active galaxies'. The Rosat observatory showed that, with possibly a thousand such objects in every square degree, the origin of the low-energy X-ray background was at last resolved.

However, the typical X-ray spectra of these active galaxies, when extrapolated to higher energies, do not match the spectrum of the diffuse background. Most astronomers believe that this puzzle could be explained if there are many galaxies harbouring hidden black holes at their centres. These massive black holes may have been formed early in the history of the Universe, and should be seen radiating copious amounts of energy at all wavelengths. However, large discs of swirling gas and dust surrounding the black holes may be very effective at blocking our view of this radiation at most wavelengths. Energetic X-rays should be able to penetrate these absorbing layers, so astronomers are keen to use XMM-Newton to check out their theories that more faint galaxies should be detectable with the improved ability to see to higher and higher X-ray energies.

The first tantalising glimpse of XMM-Newton's power to stare deeply into the Universe's past comes from an observation of the Lockman Hole. This region of sky, named after its discoverer, was selected as a location with a patch of very low absorbing material from the Milky Way, thus allowing one to look very deep into the Universe. It is also one of the best-surveyed regions by previous missions.

Figure 12 shows the image accumulated after about 30 hours of observing this area. The colours have been chosen to highlight the different X-ray energies emitted by the sources: red is used for low-energy X-rays previously seen with Rosat, whereas green and blue represent progressively more energetic X-rays. As predicted, there do seem to be additional galaxies shining through in this range.

Figure 13 shows a census of the objects seen in the highest (5–10 keV) energy range. This graph shows that as we move progressively to fainter and fainter objects (leftwards), the number of objects per square degree increases. The sensitivity of XMM-Newton in this energy range is an enormous improvement over previous observatories. This survey is already a factor of 20 better than the previous best Beppo-SAX observatory surveys in this range.

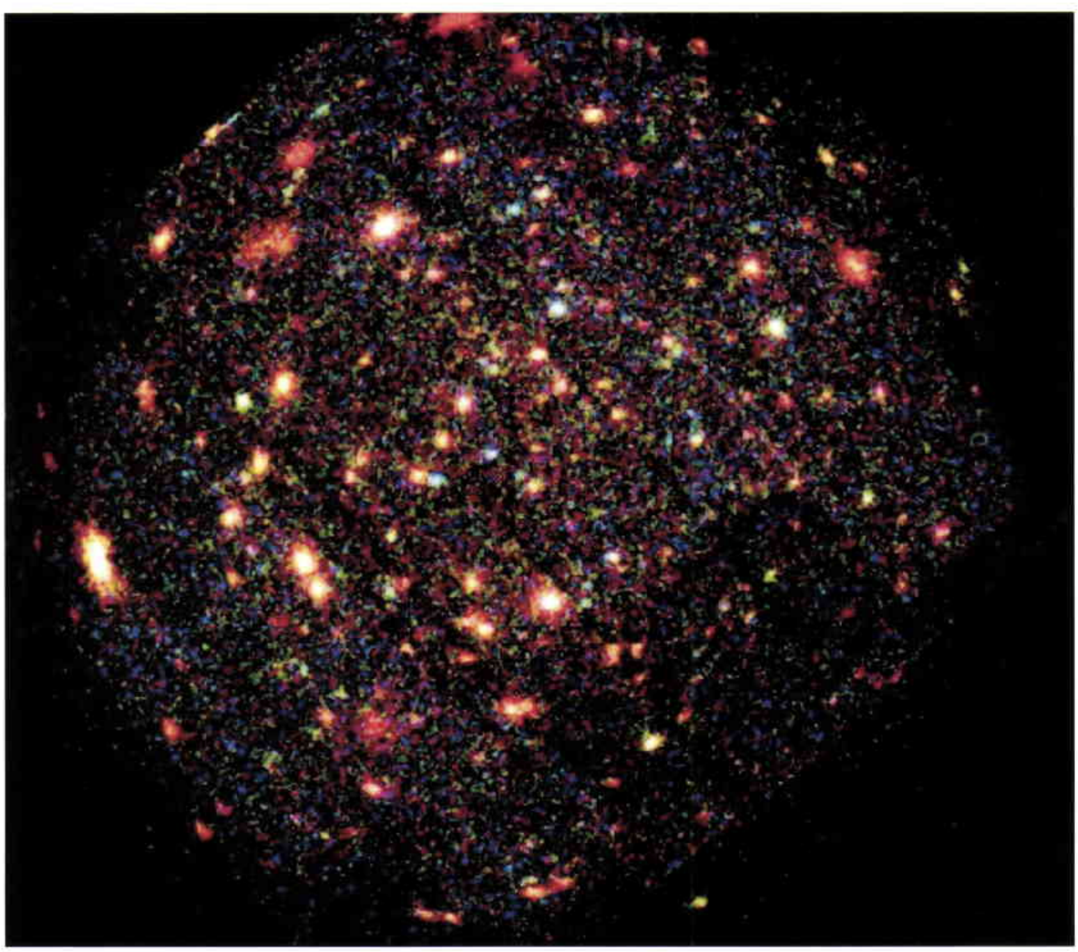


Figure 12. Combined EPIC-MOS and EPIC-PN full-energy-range image of the Lockman Hole. Red objects are low-energy (less-absorbed) sources seen clearly with previous Rosat observations. Green and blue objects represent much more energetic sources seen clearly for the first time by XMM-Newton

Initial efforts are starting to see if this behaviour can be predicted by models of the evolution of galaxies over the history of the Universe. It is clear that XMM will make a significant contribution to our understanding of the ubiquity of black holes and their substantial contribution to the previously missing energy budget of the Universe.

Among the many interesting objects that turned up in the XMM-Newton image are two slightly more diffuse red patches (lower left and upper left from the centre). One of these is a cluster of galaxies at a red shift of about 1.2 (this means we are seeing the light from a cluster that originated when the Universe was less than half its current age). XMM-Newton measurements of the temperature and mass of this cluster show it to be far more massive than most cosmologists believed clusters could ever be so early in the Universe.

The utility of the OM observations of the same fields is demonstrated in Figure 14. On the left, we see a portion of this field taken using a filter with no colour discrimination. The same area as observed by the different colour filters of OM is shown on the right. The combination of UV and optical filter images provides a false-colour image. It is evident that OM not only matches the power of large ground-based telescopes, but the addition of its ultraviolet capability provides new colour discrimination. For example, it is likely that very blue objects are galaxies undergoing an intense episode of star formation, which produces many young hot blue stars. Such information can lend considerable strength to the identifications of faint objects seen in the X-ray cameras' images.

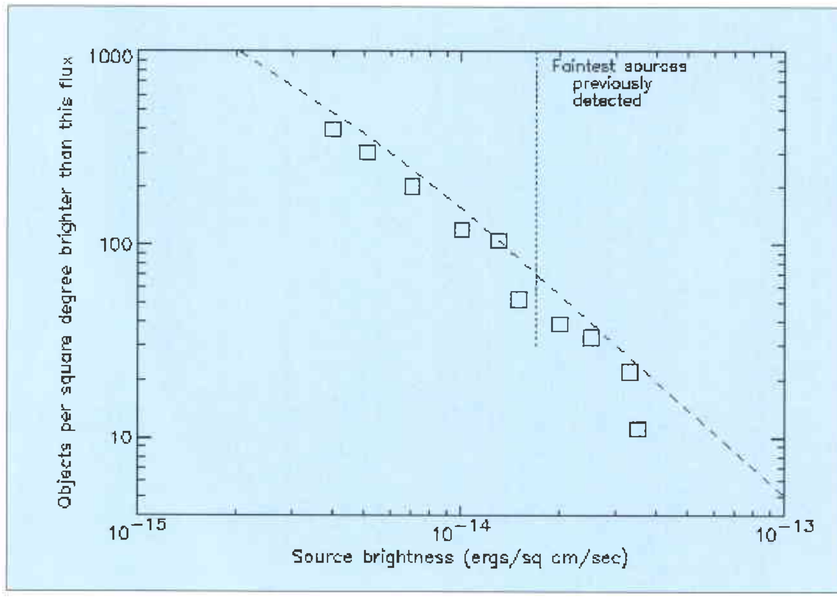


Figure 13. Density of sources in the sky in the 5–10 keV energy band. Squares represent the measured data in the XMM image, while the dashed line is a prediction based on models of galaxy evolution. The dotted vertical line indicates the limit of deep surveys conducted previously in this energy band

Conclusion

XMM-Newton's exceptional combination of instruments for spectroscopic studies has already demonstrated the power of analysing the physical conditions around stars in our cosmic neighbourhood. The phenomena of stellar supernova explosions that created the chemical building blocks of planets and life itself are being investigated even as far away as neighbouring galaxies. The details provided by this ground-breaking new generation of instruments will keep astronomers busy, trying to understand the complex distribution of hot gases. The unmatched collecting power of XMM is also being used to study the deepest parts of the Universe, challenging some of the more important theories about the structure and evolution of the Cosmos.

Acknowledgement

The authors would like to acknowledge the contributions of literally hundreds of people involved in building and operating the XMM-Newton spacecraft and its instruments. The work described above could not have been done without their dedication and professionalism.

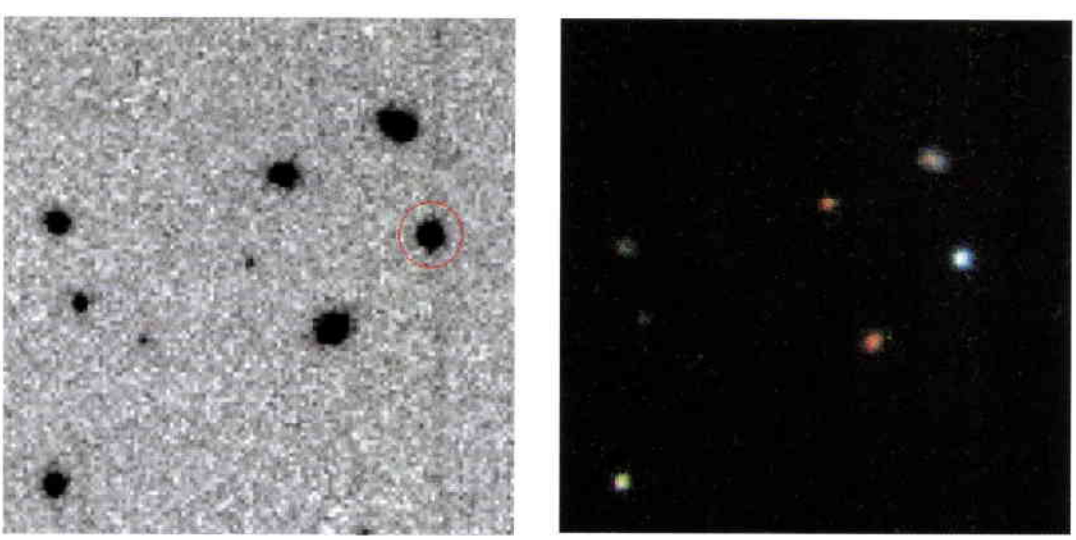
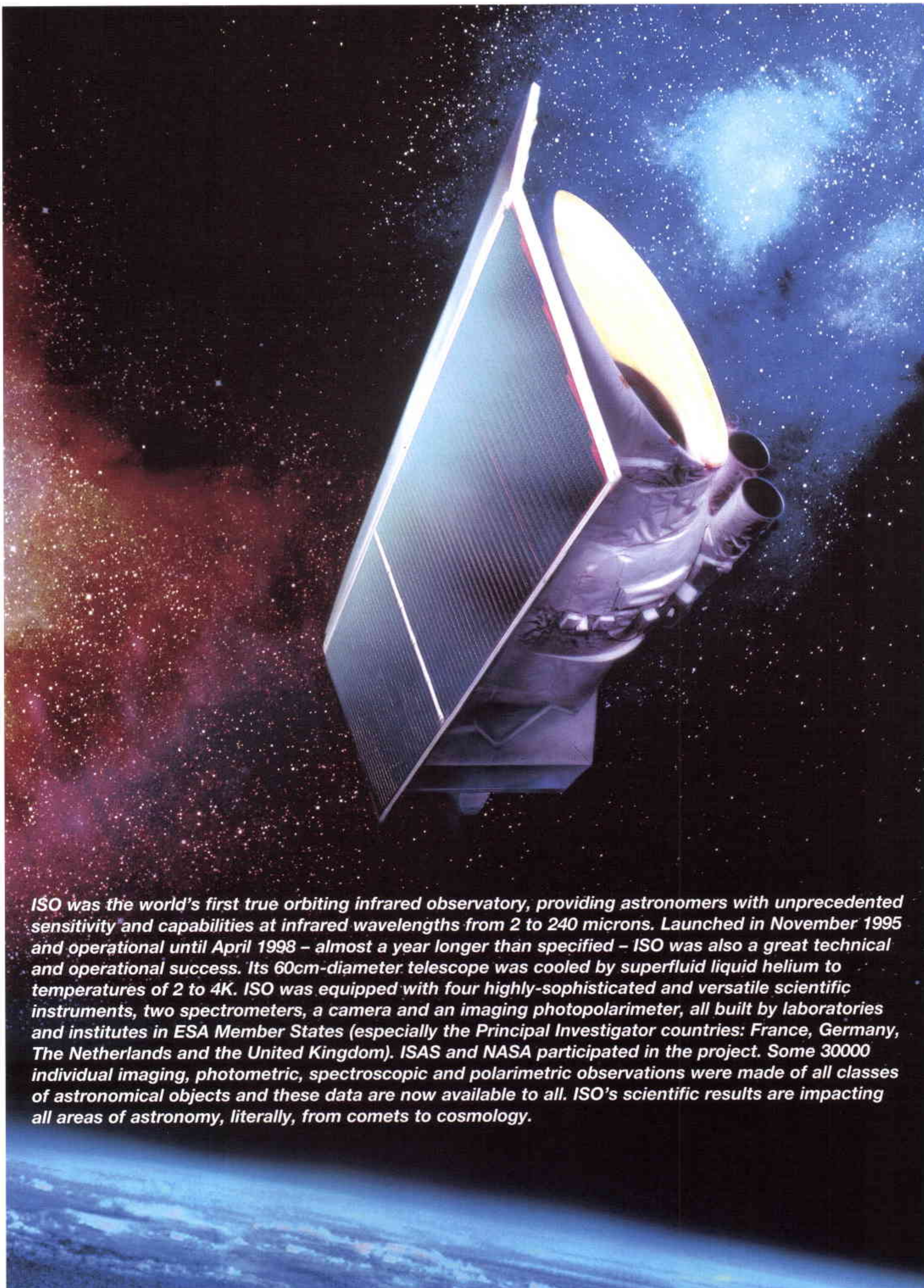


Figure 14. Small section of the Lockman Hole field in the visible range. Left: OM image using the white-light filter. Right: OM image in false colour



ISO was the world's first true orbiting infrared observatory, providing astronomers with unprecedented sensitivity and capabilities at infrared wavelengths from 2 to 240 microns. Launched in November 1995 and operational until April 1998 – almost a year longer than specified – ISO was also a great technical and operational success. Its 60cm-diameter telescope was cooled by superfluid liquid helium to temperatures of 2 to 4K. ISO was equipped with four highly-sophisticated and versatile scientific instruments, two spectrometers, a camera and an imaging photopolarimeter, all built by laboratories and institutes in ESA Member States (especially the Principal Investigator countries: France, Germany, The Netherlands and the United Kingdom). ISAS and NASA participated in the project. Some 30000 individual imaging, photometric, spectroscopic and polarimetric observations were made of all classes of astronomical objects and these data are now available to all. ISO's scientific results are impacting all areas of astronomy, literally, from comets to cosmology.

ISO* and Cosmic Water

A. Salama & M. Kessler
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ESA Directorate of Scientific Programmes, Villafranca, Spain

Water, the basic substance essential for life, has been detected by the Infrared Space Observatory (ISO) in many places throughout the Universe, including our planetary neighbours in the Solar System, clouds circling or pouring out of stars, the vast spaces between stars, and distant galaxies. We show here how these observations enable us to reconstruct the cosmic cycling of water, and its relevance to the presence of water on the Earth.

How can water be detected?
The water molecule consists of two atoms of hydrogen and one atom of oxygen, linked together in an unusual asymmetric way, with a bond angle between the two hydrogen atoms of 105 deg, rather than a symmetric 180 deg (Fig. 1). This geometry is responsible for many of its special properties, including making it a universal solvent. Like any other molecule, the atoms vibrate and rotate, but nature allows only a finite number of possibilities for the energy states of the molecule, governed by the laws of quantum mechanics. Thanks to the peculiar geometry, water can be found in many different rotational-vibrational states, and it is possible to observe a molecule changing from one of these states to another by detecting the radiation that accompanies each transition. The relative population of these energy levels depends on physical parameters such as density and temperature. The change between states is associated with an absorption (if going to higher energy levels) or emission of radiation, at specific wavelengths in the infrared or submillimetre part of the spectrum. The infrared radiation carrying the information on the physics of water in the Universe is, however, lost when it has to transit Earth's humid atmosphere after having travelled through space for millions of years. Our atmosphere is highly opaque throughout the whole infrared region of the spectrum.

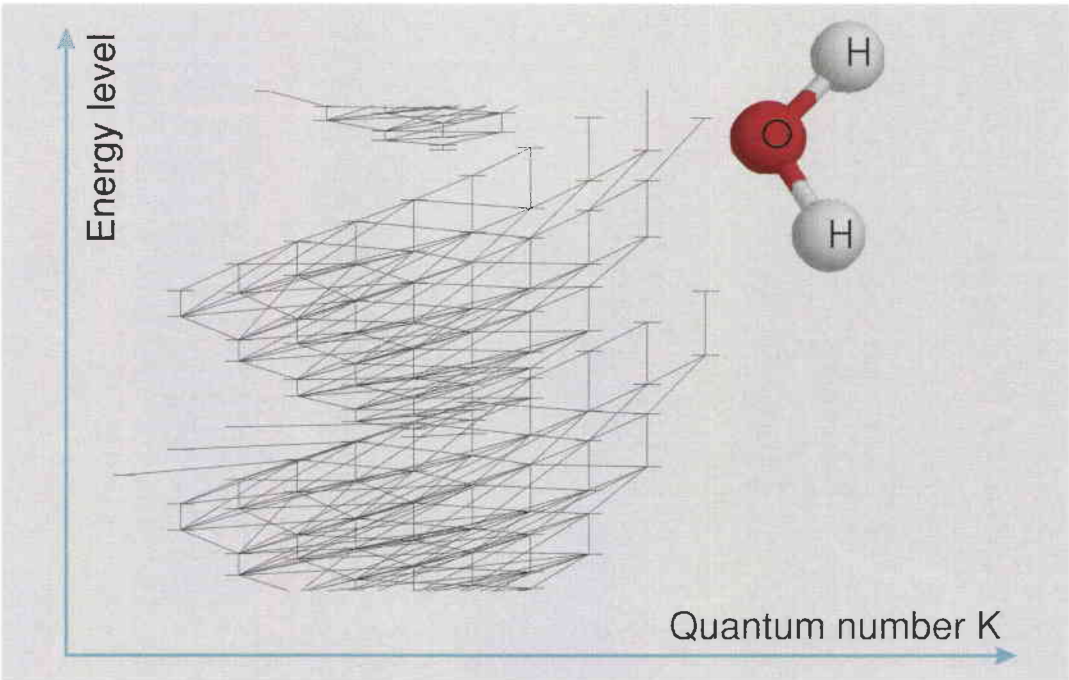


Figure 1. Energy-level diagrams for vibrational/rotational levels of the water molecule. Each level is characterised by an integer value of several quantum numbers, one of which is designated K. The transitions shown here occur in the wavelength range covered by ISO, corresponding to gas temperatures ranging from 1000 to 6000 K. Such a wealth of transitions is due to the non-linear shape of the molecule, while its symmetry causes the transitions to be divided into the two classes – those with even K are called para- while odd K are called ortho- (for simplicity, only the latter set is shown here). ISO observations have shown that the ratio of the ortho- to the para- form of the molecule in many objects is less than the equilibrium value of 3 (Adapted from K. Volk)

* Additional information on ISO, including results galleries and how to retrieve data, can be found by following links from the ISO Home Page (www.iso.vilspa.esa.es); news items are also posted at www.sci.esa.int. Previous ESA Bulletin articles have addressed: the scientific results (Kessler et al., No. 99, September 1999); the data archive (Arviset & Prusti, No. 98, June 1999); the ISO operations (Kessler, Clavel & Faelker, No. 95, August 1998); early ISO results (Kessler, No. 86, May 1996); and pre-launch descriptions of the overall mission (No. 84, November 1995).

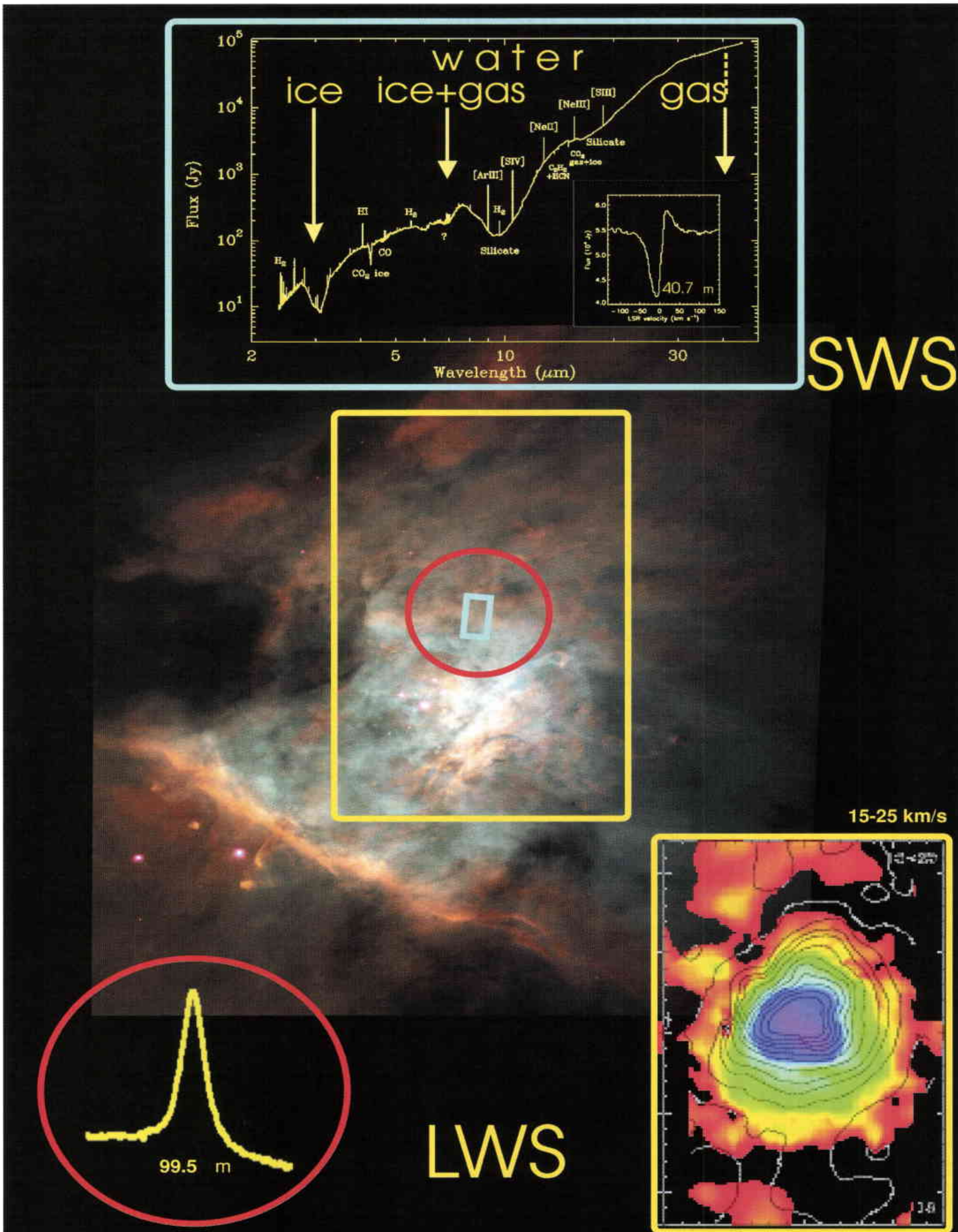


Figure 2. Water detection in the Orion nebula. The area covered by the SWS spectrometer (shown in blue) presents a wealth of atomic, ionic and molecular lines seen in Orion IRC2, superimposed on a thermal emission from warm (50 - 300 K) dust. Water lines were also detected by the LWS spectrometer (in red). The water lines are detected in emission and in absorption, indicating a complex geometry. A mapping performed with the LWS (in yellow) shows that water is present over a large area, at velocities of the order of 70 000 km/h (Credits: SWS / E. van Dishoeck, C. Wright et al.; LWS / M. Harwit, J. Cernicharo et al.; NASA/HST / C.R. O'Dell, S.K. Wong)

Some information on water in space has been retrieved from peculiar, isolated lines in the radio range, so-called 'maser lines', which occur in very small, cool regions, often close to a young star that is still being formed, but the interpretation of these lines is difficult.

ISO was the first true infrared observatory in space and provided astronomers with the direct, simultaneous detection of tens to hundreds of spectral lines of water, thereby allowing the physical conditions – the temperature, density, chemical composition – and in some cases also the dynamics of the emitting regions to be determined. Thanks to ISO's spectrometers, astronomers now know more securely how much water there is in these regions. In some cases water is present on very large scales.

How is water formed?

The ingredients needed to form water are readily available in the Universe, hydrogen being the most abundant element. It has existed since the 'big-bang', which marked the formation of the known Universe some 12-15 billion years ago. Stars, like our Sun, produce heavier elements by nuclear reactions 'burning' hydrogen in their centre. Oxygen is created in the centre of massive stars and released into space via stellar winds or supernova explosions. Heavy elements wander in space – in the colder regions, some stick together, forming grains. Interstellar dust grains are either silicate (coming from oxygen-rich stars) or carbonaceous grains (from carbon-rich stars) and are typically 0.1 microns (one ten-thousandth of a millimetre) in size. It appears from infrared measurements of distant galaxies that star formation was more frequent in the early epochs of the Universe, when it was only a billion years old.

The space between stars, known as the 'Interstellar Medium', thus contains the ingredients for water in large quantities. In order for these ingredients to actually form water, a temperature of a couple of hundred degrees above the absolute level (0 Kelvin) is required to trigger chemical reactions. The Interstellar Medium is generally cold (about 10 Kelvin), but in certain places its temperature can reach thousands of degrees, such as in the violent processes associated with the formation of stars.

Therefore, ISO was expected to find water, with an abundance of at least 1 part in 10 million hydrogen molecules (10^{-7}), and it was inferred from the above-mentioned maser lines that water could reach an abundance of one molecule per 10 000 hydrogen molecules (10^{-4}) in star-formation regions. Water was predicted to be the dominant oxygen-bearing species in warm (~1000 K) dense gas (other oxygen atoms would stick to carbon). ISO not only fulfilled its promise, but also provided previously unexpected detections of water, allowing more links to be established between the distant Universe and ourselves.

Let us now embark on a hypothetical journey through the cosmic cycle of water, as revealed by a few examples extracted from the total database of some 30 000 observations made by ISO.

Orion: a cosmic factory

The richness of the infrared spectrum, opened up by ISO's spectrometers, can be seen in the spectrum of Orion (Fig. 2). This nearby nebula ('only' 1500 light years from us) is one of the most studied molecular clouds and star-forming regions because of its brightness and proximity. A wealth of atomic and molecular lines, among them water, are visible, superimposed onto a continuum originating from the emission of warm dust (at 50 – 300 K). Large quantities of water are produced when the gas and dust undergo gravitational collapse, as part of the process leading to the formation of a star. The temperature increase in the centre of the contraction drives violent supersonic waves, travelling at more than 60 000 km/h, which increase the temperature in the outer regions, triggering the transformation of hydrogen and oxygen into water. The newly-formed water releases part of the energy via the above-mentioned rotational-vibrational transitions, and thus prevents the gas from expanding again. It was indeed expected that water would be a major 'coolant', thus promoting the collapse of clouds of gas and dust to form a star.

It has been calculated from the ISO observations that Orion is producing enough water to fill the Earth's oceans 60 times a day. Almost one hundred water lines have been detected in the central region of Orion – some in emission and some in absorption – indicative of a turbulent geometry of gas and dust. The map shown in Figure 2 led to the determination of the water distribution over a region as wide as 100 000 times the Earth-Sun distance (one Astronomical Unit, AU). The derived abundance in Orion of 10 molecules of water per million hydrogen molecules in the so-called 'ridge', increasing to 500 molecules in the centre confirmed the expectations.

Another example of the production of water over a wide, extended region is provided by Sgr B2, a huge molecular cloud located close to

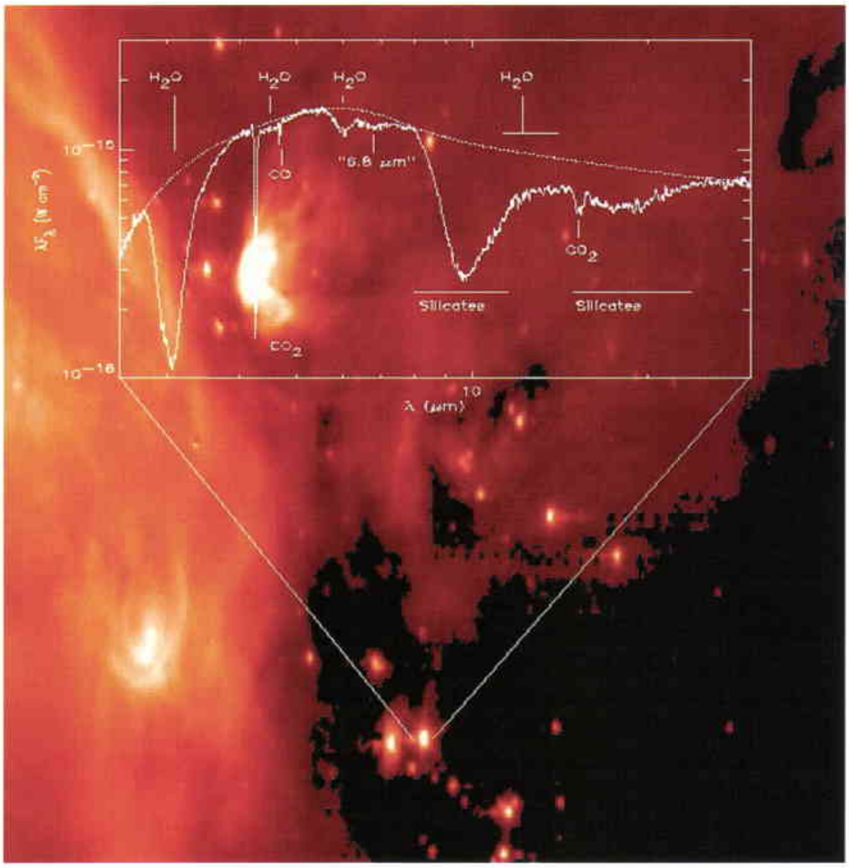


Figure 3. The low-mass protostar Elias 29 is located in the dense molecular cloud Rho Ophiuchi. It is one of the two bright IR spots in the centre of this composite image obtained with the ISOCAM using 6 and 16 micron filters. The absorption spectrum of the interstellar material is dominated by the water-ice bands at 3 and 6 micron due, respectively, to the ice molecule O-H bond variation with inter-atomic distance (stretching mode) and the varying angle between the two hydrogen atoms as seen from the central oxygen atom (bending mode) (Credit: ISOCAM/SWS / A. Boogert et al.)

the centre of our Galaxy. There, an abundance of 10 molecules of water per million hydrogen molecules was derived over a region 150 times larger than in Orion. NASA's Submillimetre Wavelength Astronomical Satellite (SWAS) – launched after ISO – probed cooler regions, providing the measure of 10^{-8} (10 molecules of water per billion hydrogen molecules) in quiescent clouds.

What happens to the newly formed water molecules? They survive the imminent destruction from the strong ultraviolet radiation emitted by the embryonic star, thanks to the shielding provided by the dust. Away from the star, water molecules stick onto grains as ice. This cosmic 'dirty snow' will then stay in the same system or travel in space until it is eventually incorporated into the formation of another stellar system.

YSOs (Young Stellar Objects)

Once a star is born, it is called a YSO (Young Stellar Object) by astronomers. The dust in the surroundings of the star is heated to a few hundred degrees, thus providing a continuum against which the cooler foreground species can be seen in absorption. An example is provided by the ISO spectrum of Elias 29 (Fig. 3). The water ice bands at wavelengths of 3 and 6 microns dominate the spectrum. Fingerprints of many other species are present. In fact, ISO has provided the first complete, unbiased census of a variety of interstellar ices, thus giving an important impetus to laboratory research for the correct interpretation of the spectra. Water in the gas phase is also detected, closer in to the star where the temperature is high enough to expel the water from the grains or to trigger further formation of water molecules. ISO has observed water lines in a number of YSOs (Fig. 4). The derived abundances for the gas and solid phases show a dependence on temperature, which points to different evolutionary stages as the envelopes expand and cool. The ISO observations thus put constraints on the models developed for

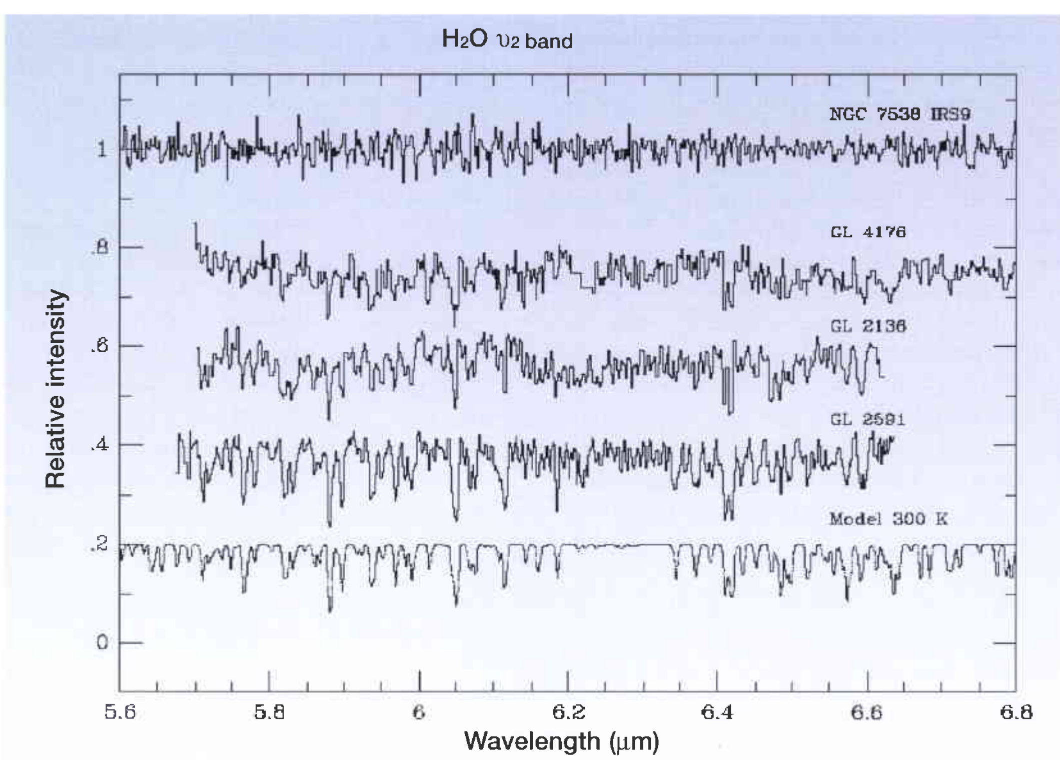


Figure 4. Spectra of a few YSOs in the bending mode band of water at 6 micron. Note how well the observed spectra (first 4 rows) are matched by the model (last row), which assumes warm (300 K) water vapour (Credit: SWS / E. van Dishoeck & F. Helmich)

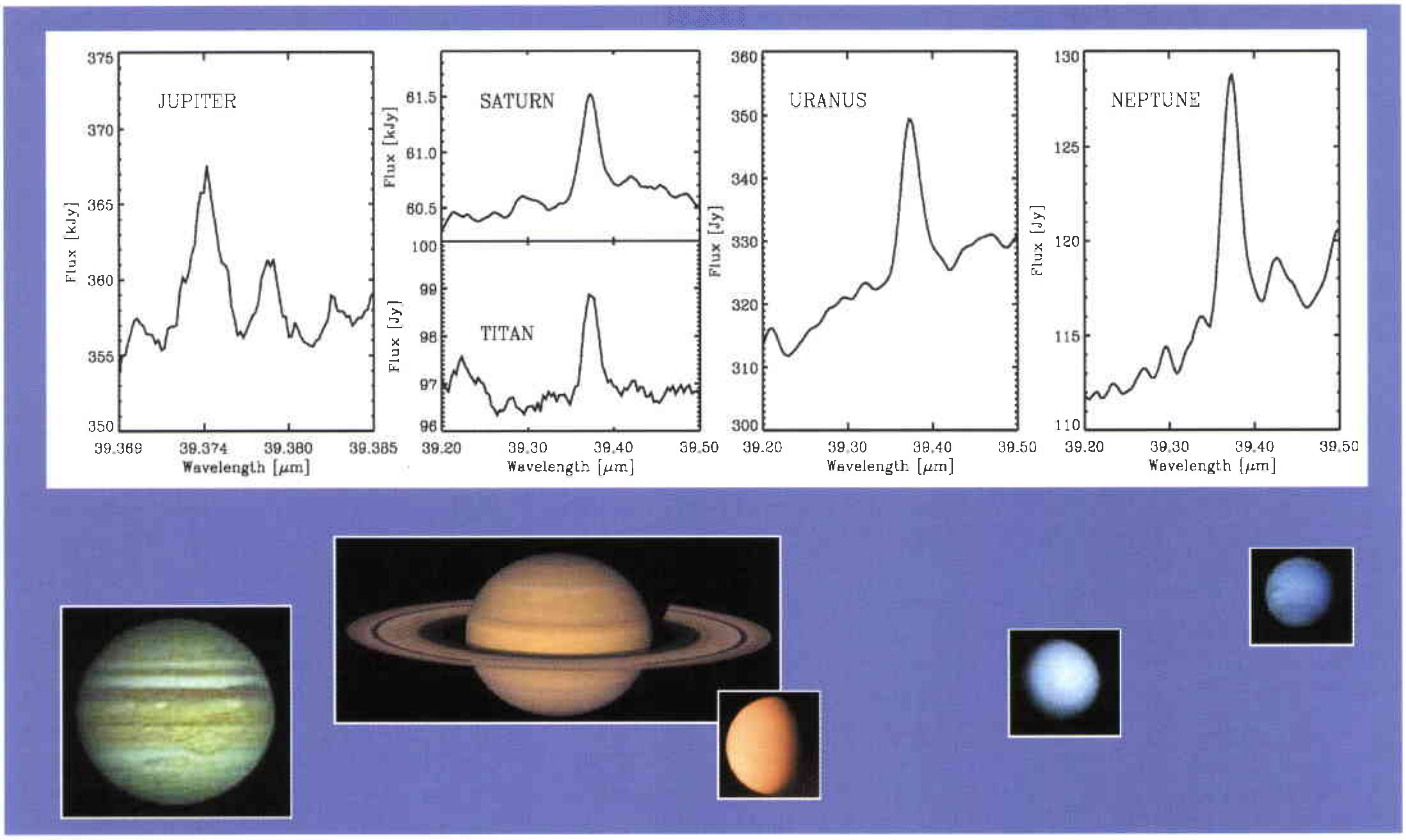


Figure 5. Detection of water vapour in the upper atmospheres of the Giant Planets and Saturn's moon Titan
(Credit: SWS/ H.Feuchtgruber, Th. Encrenaz, A. Coustenis et al.)

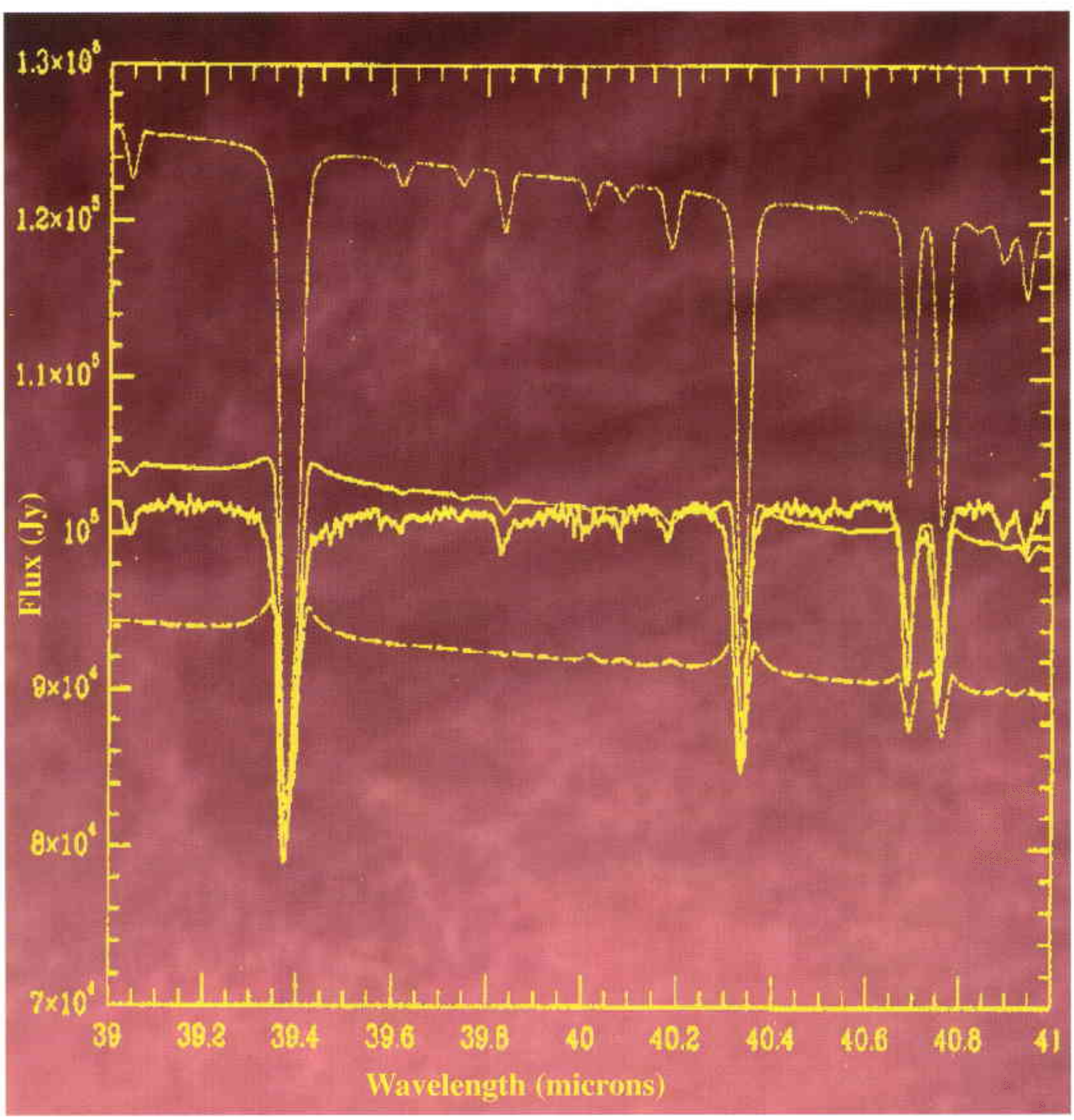


Figure 6. ISO detections of water lines in the Martian atmosphere, overlaid on a Mars Pathfinder image of Martian clouds. The ISO results are best modelled with a tenuous (~15 ppt-micron) layer of water clouds located close to the surface (~13 km altitude), thus confirming the results obtained by Mars Pathfinder
(Credit: SWS / Th. Encrenaz et al., NASA / Pathfinder)

YSOs, determining the relative contributions of the envelopes and shocks as water formation carriers. It is interesting to note the similarity in the composition of YSOs and cometary ice, for instance in W33A and Comet Hale-Bopp, which exhibit 82% and 72% water ice, respectively.

Formation of planets

Planets appear to form through an agglomeration of material from the surroundings of a newly born star. The remaining dust (not processed into planets) would remain at the outskirts of the newly formed solar system, containing water ice. Let's confront this theory with the ISO observations of the Solar System.

Our Solar System

The most surprising results from the ISO observations of the Solar System are the detection of water in the upper atmospheres of all of the giant planets and on Saturn's moon Titan (Fig. 5). Water has also been detected close to Mars' surface (Fig. 6). Indeed, water is expected to have been present in the Solar System since its formation, as we have seen that water is abundant in the Interstellar Medium. However, the water incorporated in the planets is expected to condense in clouds, as we see on Earth. Therefore, there must be an extérnal source of water. The similar influx observed for the giant planets and Titan favours a real external source, although the sputtering of the icy rings could also play a role; the influx of water (which on Saturn is of order 4 – 70 kg/s) is attributed to interplanetary dust and comets. An example of such impacts is provided by Comet Shoemaker-Levy 9, which broke-up and impacted in Jupiter's atmosphere in 1994, releasing 2 million tons of water.

Comets are distributed in two groups: the short-period comets, believed to originate in the region close to Neptune's orbit (the so-called 'Kuiper Belt'); and the long-period comets, believed to come from a sphere at a radius of about 50 000 AU (the so-called 'Oort Cloud'). Being so far away from the Sun, comets are believed to maintain the pristine composition of the pre-solar nebula. ISO observed comets from both groups, detecting water, CO and CO_2, with gas production rates increasing as the comets were approaching the Sun, as expected. Water ice has also been observed, and the gas and ice production rates are similar, pointing to a scenario in which the water vapour comes from the evaporation of ice. The water released by Comet Hale-Bopp was measured by ISO at 2.9 AU to be 10 ton/s (Fig. 7).

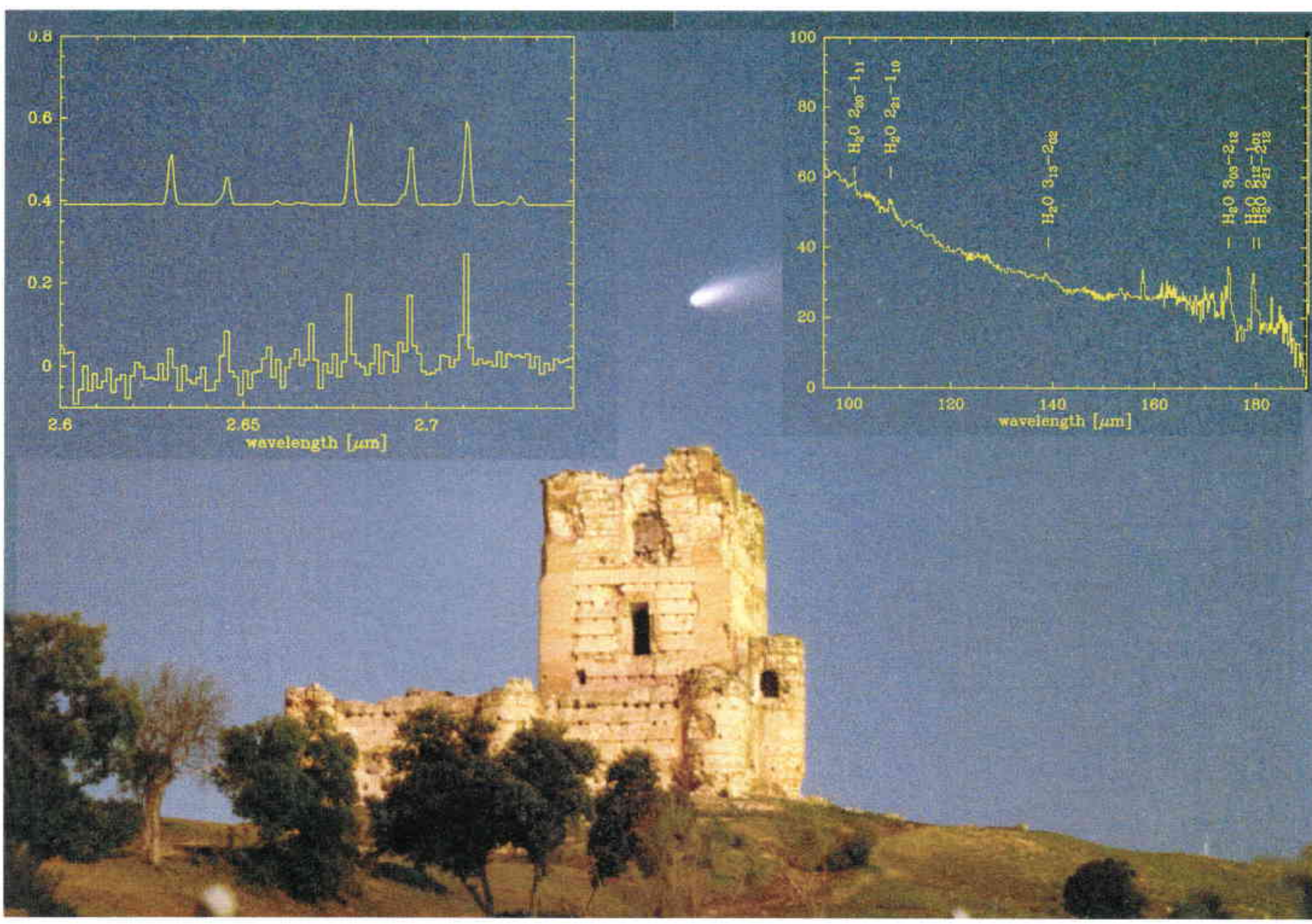
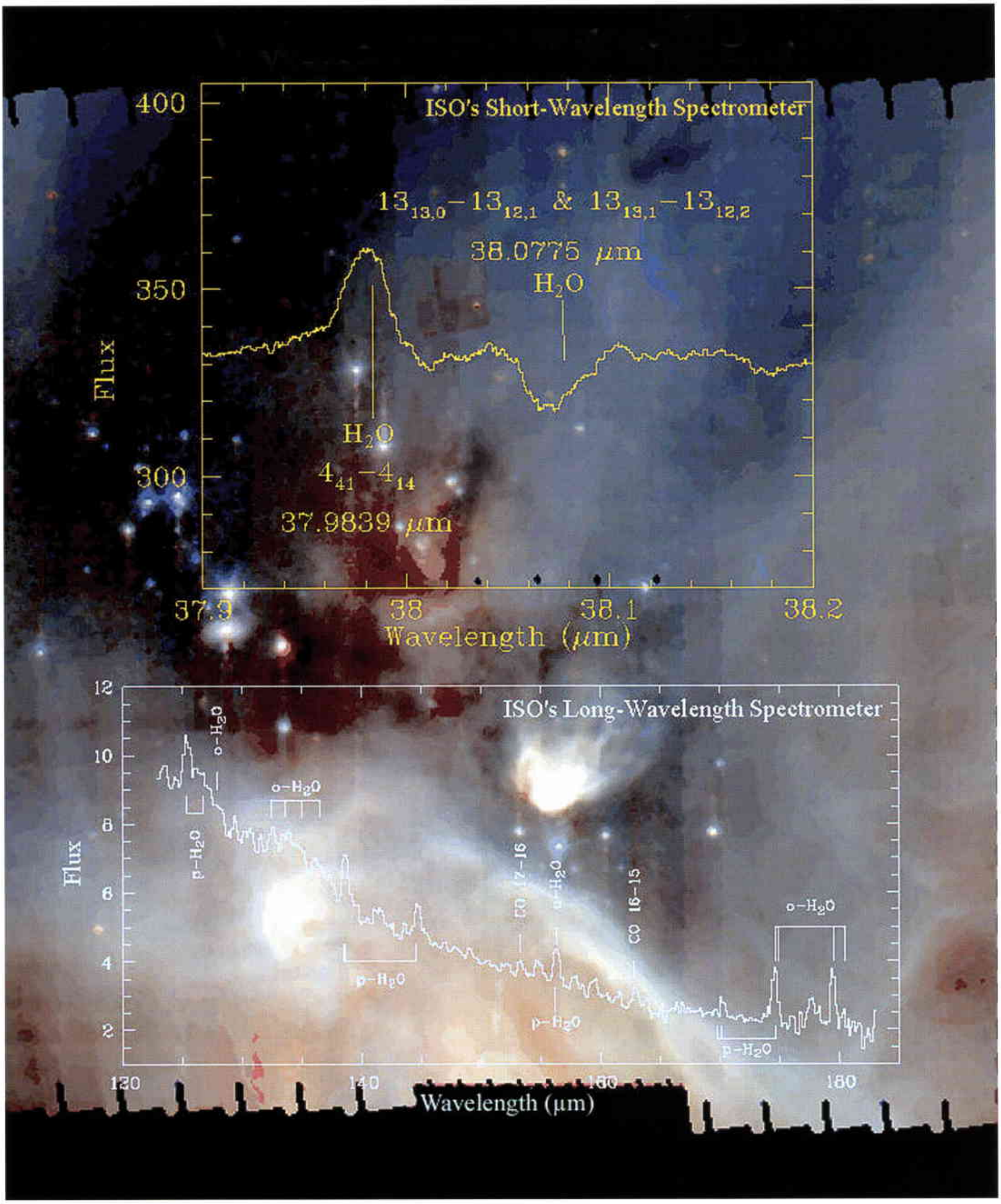


Figure 7. SWS and LWS spectra of Comet Hale-Bopp, showing various lines of water vapour (Credit: SWS / LWS / J. Crovisier et al.) The background image shows the comet above the castle at ESA's VILSPA ground station near Madrid, from which ISO was operated (Credit: K. Leech)



ISO observations therefore address the question of the origin of water on Earth. The scenario by which water originates from the impact of external bodies is gaining weight, while some water could also have been released by the inner rocks in the form of steam during the numerous volcanic eruptions on the young planet Earth. The influx of water currently inferred from ISO observations of the giant planets and Titan is compatible with the observed influx of interplanetary dust (also of cometary origin) at 1 AU. The amount of water present on Earth is compatible with an impact frequency for large comets on Earth equivalent to about 1 impact per millennium over the first billion years of the Solar System, which is not unreasonable.

Figure 8. Detection of water vapour in the vicinity of stars: W Hydrae (Credit: SWS /LWS / M. Barlow et al.) In the background, an ISOCAM image of the dark star-forming region Rho Ophiuchi.

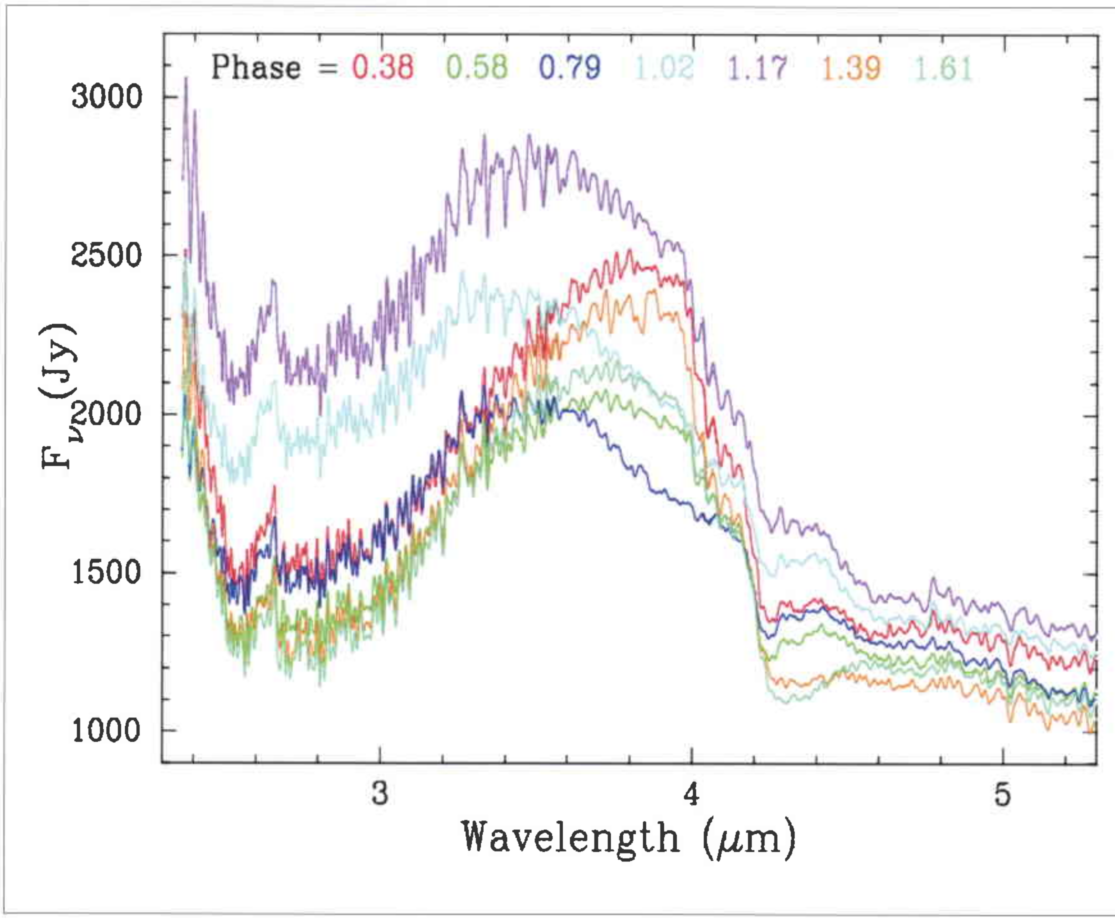


Figure 9. The water spectrum in T Cep shows a variation that correlates with the star pulsation (Credit: SWS / I . Yamamura, M. Matsuura, T. Tsuji et al.)

What happens to water when a star dies?
When the hydrogen fuel becomes depleted in the interior of a star, more is used from the outer parts. This starts a process of expansion of the star, until it becomes a red giant. It is expected that this will occur with our Sun in 5 billion years' time. One of the last evolutionary stages of stars with low to intermediate masses (ranging from one to eight times the mass of the Sun) is called the Asymptotic Giant Branch (AGB). In the AGB phase, stars are red giants with effective temperatures of typically 3000 deg and radii several hundred times the radius of the Sun. The star's structure is very complicated, with several layers of different compositions, resulting in tremendous instabilities. Quite often, AGB red giants are observed as variable stars, like the star Mira, which vary in the visible by several magnitudes with periods of typically one year. These stars lose mass into the Interstellar Medium via the pulsation mechanism, with rates ranging from one E-7 to E-4 solar masses per year at velocities of 36 000 km/h.

ISO has detected water lines in the outer atmospheres of several AGB stars (e.g. W Hya, shown in Fig. 8) and, unexpectedly, also around a hotter star (μ Cep). This is best modelled assuming concentrations of hot (1000–2000 K) water vapour located a few stellar radii from the star. In some cases, the water emission appears to follow the stellar pulsation (Fig. 9). ISO's detection of water around stars is forcing theoreticians to expand their stellar modelling to the outer layers, by means of dynamical models.

The future
ISO has provided – for the first time – a complete overview of the incredibly rich spectroscopy in the infrared and has shown the ubiquitous presence of water in space, even in other galaxies such as Arp 220, but this is only the 'tip of the iceberg'. More details and, possibly surprises, remain to be found in the ISO data, even as other facilities are being prepared. Greater detail and better spatial and spectral resolution (providing more information on the dynamics) are expected to come from the ESA Cornerstone FIRST mission (to be launched in 2007), SIRTF (2002 launch), SOFIA (to be operated from 2002), and NGST (2009).

Acknowledgement
The results described above are the work of a large number of astronomers, who for reasons of readability have not been individually credited throughout the article. The world-wide astronomical community is also thanked by the authors for their enthusiastic use of ISO data, without which this article would not have been possible.

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MWR and DORIS – Supporting Envisat's Radar Altimetry Mission

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Following on from the great success of its ERS-1 and ERS-2 satellite missions, which have contributed to a much better understanding of the role that oceans and ice play in determining the global climate, ESA is currently preparing to launch Envisat, the largest European satellite to be built to date.

The Envisat altimetric mission objectives are addressed by the Radar Altimeter instrument (RA-2), complemented by the Microwave Radiometer (MWR), used to correct the error introduced by the Earth's troposphere, and by the Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) instrument. DORIS has been developed by CNES, and is already operational on several satellites. It will measure Envisat's orbit to an unprecedented accuracy, thereby serving as a major source of the improved performance that the RA-2 system will be able to achieve.

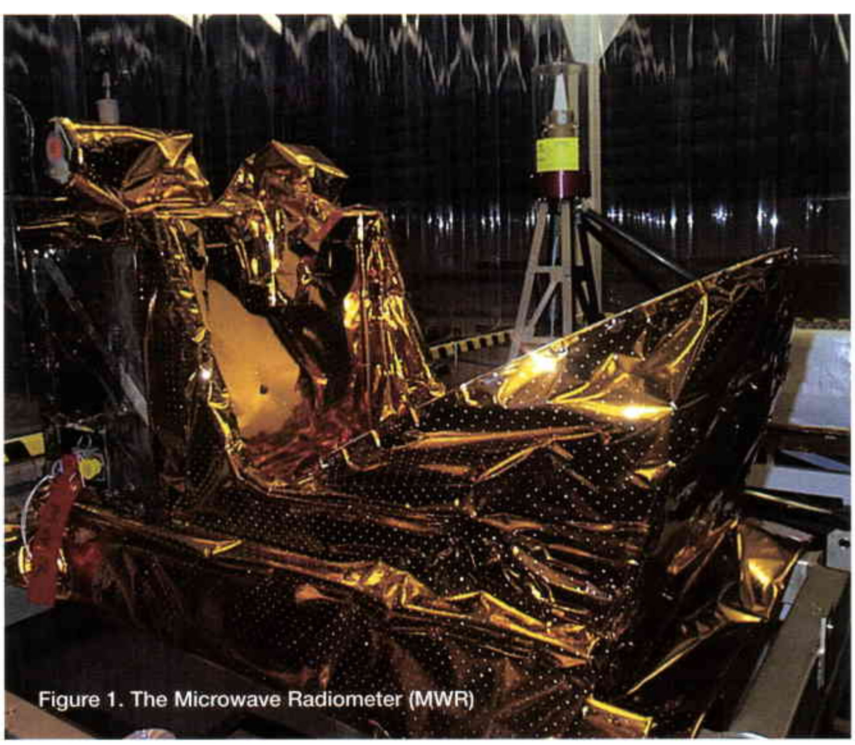


Figure 1. The Microwave Radiometer (MWR)

MWR

The mission

The Microwave Radiometer (MWR) is a two-channel passive radiometer operating at 23.8 and 36.5 GHz based on the Dicke principle. By receiving and analysing the Earth-generated and Earth-reflected radiation at these two frequencies, the instrument will measure the amount of water vapour and liquid water in the atmosphere, within a 20 km-diameter field of view immediately beneath Envisat's track. This information will provide the tropospheric path correction for the Radar Altimeter. The MWR measurements can also be used for the determination of surface emissivity and soil moisture over land, and in support of studies on surface energy budget and atmospheric and ice characterisation.

Instrument operation

The nadir-pointing antenna receives radiation at 23.8 and 36.5 GHz in linear polarisation. The antenna subsystem includes a 60-cm aluminium reflector with a focal length of 350 mm and an offset angle of 47 deg. Two feeds are used such that the 23.8 GHz channel is pointing in the forward direction and the 36.5 GHz channel in the backward direction, with a footprint of about 20 km diameter for each beam. These frequencies are separately routed into the RF front-end, where a two-point calibration scheme is adopted, with hot and cold references.

The deep cold-space measurements will be accomplished via the sky-horn feed, while the on-board calibration reference load, maintained by the thermal control system at the instrument's physical temperature, provides the hot reference.

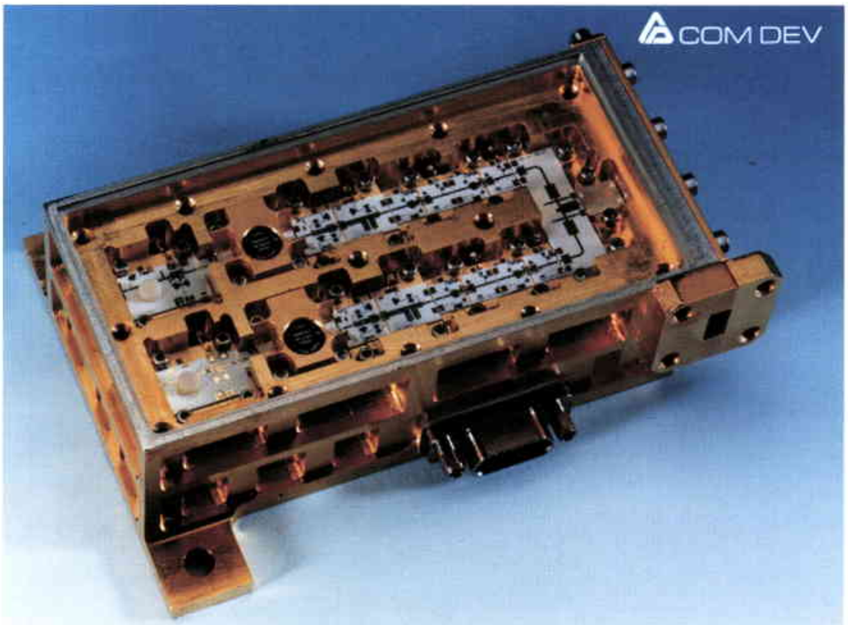
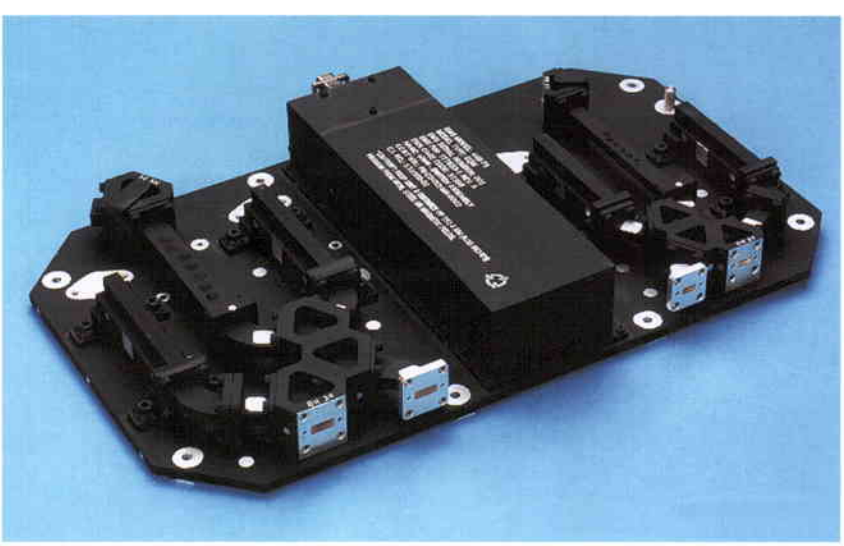


Figure 2. The 36.5 GHz Dielectric Resonator Oscillator (DRO) (courtesy of COMDEV)

The signals are down-converted in a mixer-amplifier subassembly, using the 23.8 and 36.5 GHz signals generated by Dielectric Resonator Oscillators (DROs). Both the RF front-end and the DRO's design and technology have been space-qualified for MWR. The intermediate-frequency (IF) and the analogue boards are used to process the down-converted radiometric signals; both modules are located within the Central Electronics Unit (CEU). The IF module consists of an input filter to define the bandwidth, followed by an RF amplifier chain and a square-law detector. The input signal is 500 MHz bandwidth noise, square-modulated by the Dicke frequency (1276 Hz). The analogue switches performing the detection can be opened by telecommand to avoid disturbances produced by the ASAR/RA-2 instruments. The signal is digitised in 64 bits every 150 msec.

Figure 3. The MWR radio-frequency (RF) front-end (courtesy of EMS)



The following calibration cycle is executed every 38.4 s: Hot Load Calibration (two measurements), Sky Horn Calibration (two measurements), Offset Calibration (two measurements), Main Antenna Signal (250 measurements). Alternative calibration periods of 76.8, 153.6 and 307.2 s can be selected by command.

The instrument is controlled by the common (MWR-DORIS) Instrument Control Unit, which handles the On-Board Data Handling (OBDH) interface protocol, exchanging macro commands and telemetry data. The instrument has independent thermal-control elements (heaters and thermostats) to give its electronic circuits optimum performance.

Absolute calibration has been performed at the Remote Sensing Instrumentation Meteorological Office, in Farnborough (UK). The absolute uncertainties in the brightness temperatures of the targets used were + 0.10/-0.00 K at minimum and +0.05/-0.09 K at maximum temperatures (an improvement with respect to what could be achieved for ERS-1 and 2). A detailed model of the instrument has been developed and has been validated during the calibration campaign, at instrument radiator temperatures of 0, 10, 20, 30 and 40°C. The Fixed- and Variable-Temperature Targets were used in the ranges of 85 K and 85-300 K, respectively

The instrument performance figures are presented in Table 1, which shows that the results are better than the specifications.

The MWR instrument was the first Envisat instrument to be delivered, back in September 1997. It has since been integrated into the MWR/DORIS composite and mounted on the spacecraft. Thereafter It has performed successfully in all of the satellite tests that have been conducted.

The ground segment

The received MWR data are packaged into Level-0 products and ingested (together with the RA-2 Level-0 and DORIS products) into the RA-2/MWR processor. No separate higher level MWR products are to be generated. The MWR Level-1b (brightness temperature) and the Level-2 information (wet tropospheric path delay) is embedded as a Measurement Data Set (MDS) within the RA-2/MWR Level-1b and Level-2 products (see article titled 'The Envisat Radar Altimeter System' in ESA Bulletin No. 98).

The path correction due to the wet tropospheric component is estimated on the basis of the two brightness-temperature measurements (at 23.8 and at 36.5 GHz) from the MWR and from the σ_0 information coming from the Radar Altimeter. This gives a residual inaccuracy of 1÷2 cm (comparable to that achievable by a three-frequency radiometer).

Acknowledgement
The MWR instrument was developed under the leadership of Aleniaspazio, with equipment provided by Austrian Aerospace, ComDev, Contraves Italiana, EMS, Millitech and Schrack.

DORIS

The system

The DORIS system (Doppler Orbitography and Radiopositioning Integrated by Satellite) 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 for very precise orbit determination. Beyond its initial mission objectives, the DORIS system can also fulfil other needs, such as precise ground-beacon position determination (e.g. for measuring tectonic movements), provision of Earth-rotation parameters, measurement of Earth-centre position, improvement of Earth-environment models (e.g. gravity field, global ionosphere mapping), and real-time orbit determination.

The DORIS system was designed and optimised to provide high-precision orbit determination and beacon positioning. It was developed within the framework of the Topex/Poseidon oceanographic altimetry mission and has been operational since 1990, when the Spot-2 satellite was launched with the first DORIS receiver onboard.

DORIS is an up-link 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. The core of the system is the beacon network distributed homogeneously over the Earth. The dual-frequency signals at 400 MHz and 2 GHz emitted by the beacons are used by the receivers onboard the various satellites to perform Doppler measurements. The DORIS permanent network includes 54 beacons (Fig. 4) hosted by institutes from more than 30 countries. More than 20 beacons are co-located with other precise-positioning systems to allow cross-calibration.

Each site is equipped with a beacon package that includes:
- a dual-frequency 400 MHz and 2 GHz transmitter (including an ultra-stable oscillator)
- an omni-directional bi-dual-frequency antenna, with a battery pack to provide autonomy of supply
- a meteorological package providing temperature, pressure and humidity measurements, used to correct for tropospheric effects.

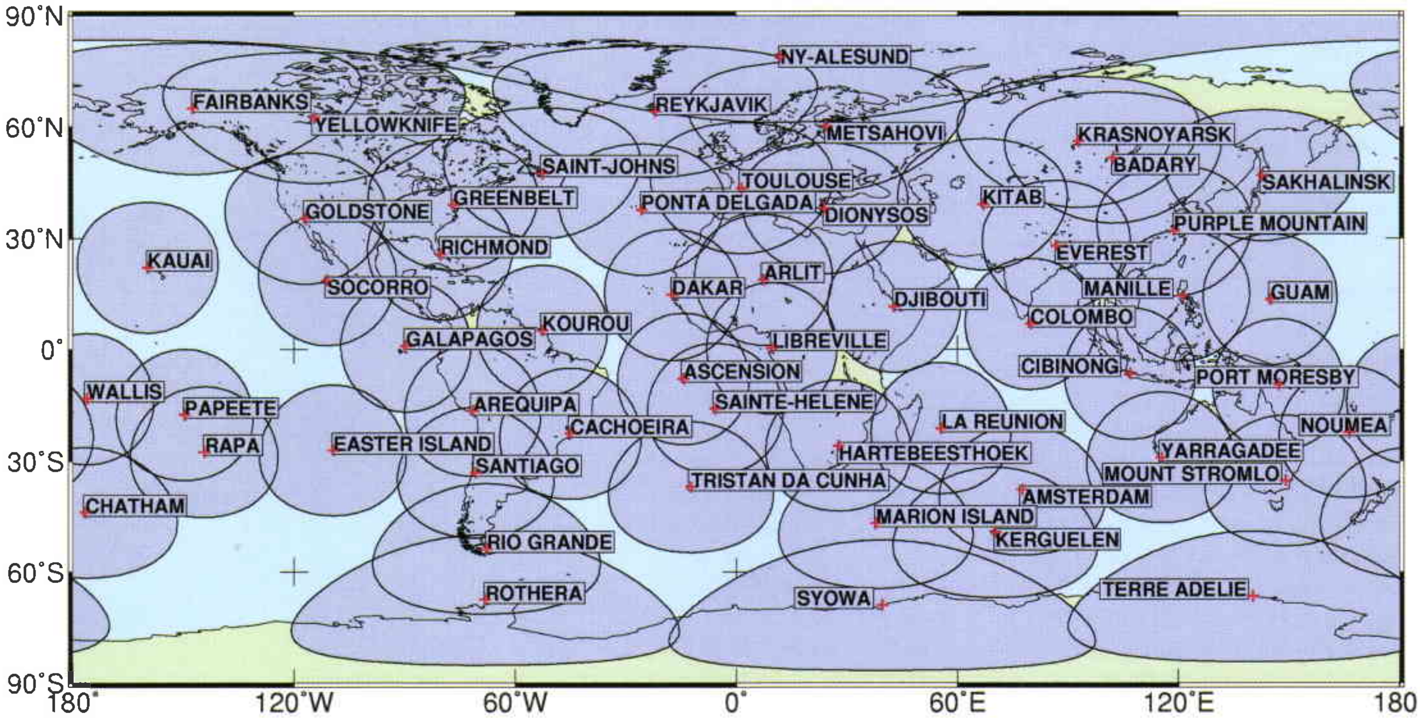
Table 1. MWR performance summary

Performance	*Requirement*	*Achievement*
Radiometric Sensitivity	< 0.6 K	0.4 K
Radiometric Stability	< 0.6 K	0.4 K
Radiometric Accuracy (after calibration)	< 3 K at Ta = 300 K	1 K at Ta = 300 K < 3 K at Ta = 85 ÷ 330 K
Dynamic Range	3 K to 300 K	3 K to 330 K
Non-Linearity	< 0.5 K	0.35 K
Centre Frequency Stability	< 0.75 MHz / °C	< 0.2 MHz / °C
Antenna Radiation Efficiency	> 93 %	97 % worst case
Antenna Main Beam Efficiency	> 89 %	94 % worst case
Antenna 3 dB Beamwidth	< 1.7 °	1.5°
Instrument Mass	< 30 kg	24 kg
Operational Power	< 50 W	18 W

The beacons transmit a narrow-band ultra-stable signal plus auxiliary data: beacon identifier, housekeeping data, meteorological data, and time-tagging reference data. Presently, two master beacons located in Toulouse (F) and Kourou (Fr. Guiana) are connected to the control centre to allow data uploads to the onboard package. They are also linked to an atomic clock to allow synchronisation of the DORIS system with international reference time.

The DORIS onboard package for Envisat includes: a receiver performing Doppler measurements and receiving auxiliary data from the beacons, a dual-frequency omni-directional antenna, an ultra-stable oscillator, and a two-channel receiver (with DIODE navigator capability as part of the onboard software). The dual-frequency receiver allows ionospheric corrections to be made.

The DORIS control and processing centre, also located in Toulouse (F), is responsible for beacon network monitoring, onboard package monitoring and programming, science telemetry acquisition and pre-processing, technological archiving, precise orbit determination, and beacon positioning. This centre is included in the SSALTO (Orbitography and Altimetry Multi-mission Centre) CNES ground segment. The interfaces between SSALTO and the Envisat Flight Operations Segment (FOS) and Payload Data Segment (PDS) have been defined to meet all of the Envisat mission requirements.



ENVISAT Elevation: 12 deg, Altitude: 800 km

Figure 4. The DORIS ground network

Instrument performance
For Envisat, the accuracy of the real-time orbit provided by the DORIS/DIODE onboard software has been specified as 1 m (three axes). The performance of the DIODE software already flying on Spot-4 and the improvements that have been tested on the ground indicate that this level of accuracy should be achieved without any difficulty. Indeed, the performance of the onboard DIODE real-time navigator has already been estimated at 40 cm from various simulations of the radial component of Envisat's orbit. The 30 cm-level is expected to be reached using an upgraded version of the software (see below).

The accuracy for the radial component of the offline precise orbit has been specified as 10 cm, with the even more challenging figure of 3 cm often quoted as a goal. Experience gained with the Topex/Poseidon and Spot satellites and appropriate simulations indicate that the 10 cm specification can be achieved without major difficulty, whereas the 3 cm goal is a challenge that the Envisat Precise Orbit Determination team will actively pursue.

The DORIS/DIODE onboard capability
The version of DIODE that will fly on Envisat is improved with respect to the Spot-4 version in that it takes into account: the Earth's gravity field up to 40°x40°, the Sun's and the Moon's attractions with a simplified ephemeris model, the solar radiation pressure using a simple model of the spacecraft, and empirical and adjustable once per revolution accelerations to absorb residual errors.

In addition, several new functions have been designed and already extensively tested on the ground:

- *Self-initialisation:* Without any orbital information, the DORIS receiver can perform measurements by simply scanning around an average frequency. DIODE will be able to estimate the spacecraft's position without needing initial conditions sent from the ground ('lost in space' scenario). The non-linear behaviour of the equations of motion is solved by using two separate filters, which process the measurements from four passages. The two filters are based on two different (one crude and one more accurate) models. The resulting orbit (generally with an accuracy of a few metres) is then provided to the standard filter for the final convergence.
- *Self-programming:* Normally, DIODE uses its estimation of the orbit to inform the DORIS receiver about the next visible station and its Doppler shift every 10 s. The accuracy is such that these predictions can be used by the receiver itself to self-programme the next station to be received. A selection algorithm is added for the cases in which several beacons may be visible simultaneously.

Also, a time-determination function now exists for all versions of DIODE that is accurate to within a few microseconds and can therefore be used on the ground and/or by the spacecraft's payloads and central flight software. The Envisat ground segment will therefore use DIODE outputs for accurate real-time product generation.

The ground network

The next generation of DORIS beacons (third generation) will have the ability to transmit their signals on slightly shifted frequencies with respect to the nominal system frequencies. This will avoid the risk of 'Doppler collisions' when the DORIS system is used from high-altitude orbit, and will allow more DORIS beacons to be used in a given region.

Another major feature of these third-generation beacons is that they broadcast the current date (year/month/day/hour/minute/ seconds) in Time Atomic International (TAI) format. It allows the in-flight DORIS instruments to perform their initialisation process – from equipment turn-on to satellite position, velocity and time estimation – fully autonomously, without any ground commanding or uploading.

Beacon data transmission (synchronisation word, auxiliary data, uploading in case of master beacons) is performed according to a 10 s sequencing. This sequencing is synchronised with respect to TAI to within ± 1 s to guarantee correct reception of these beacon data by the in-flight instruments.

DORIS's impact on Envisat mission objectives

Precise orbit determination

When designing an observing system, one has first to identify the signals within the scope of the observation. Focusing on ocean dynamics, it is clear that the corresponding signal has a wide spectrum in both space and time:

- Mesoscale eddy features, with a typical amplitude of the order of 5 to 20 cm, a spatial scale of the order of 100 to 300 km, and an associated temporal scale from a few days up to months or years.
- Seasonal signals of the order of 10 to 15 cm, varying mainly on a hemisphere basis.
- Inter-annual signals such as the El Niño phenomenon, with a typical amplitude of 20 cm and time scales ranging from several weeks to months (Fig. 5).
- Very long time scale variations in mean sea-level, with magnitudes of some 1.5 mm/yr.

Satellite orbit error has been the bane of oceanographers, who analyse altimetry data quantitatively. To overcome this difficulty, altimeter users have pinned their hopes on very efficient error-reduction methods, particularly for ocean mesocale recovery. For long-wavelength ocean signals, however, even the most sophisticated orbit error-reduction methods are not satisfactory, and will never replace very precise orbit measurements, in which DORIS can play a major role.

Climate-change studies

Within the climate-change research framework,

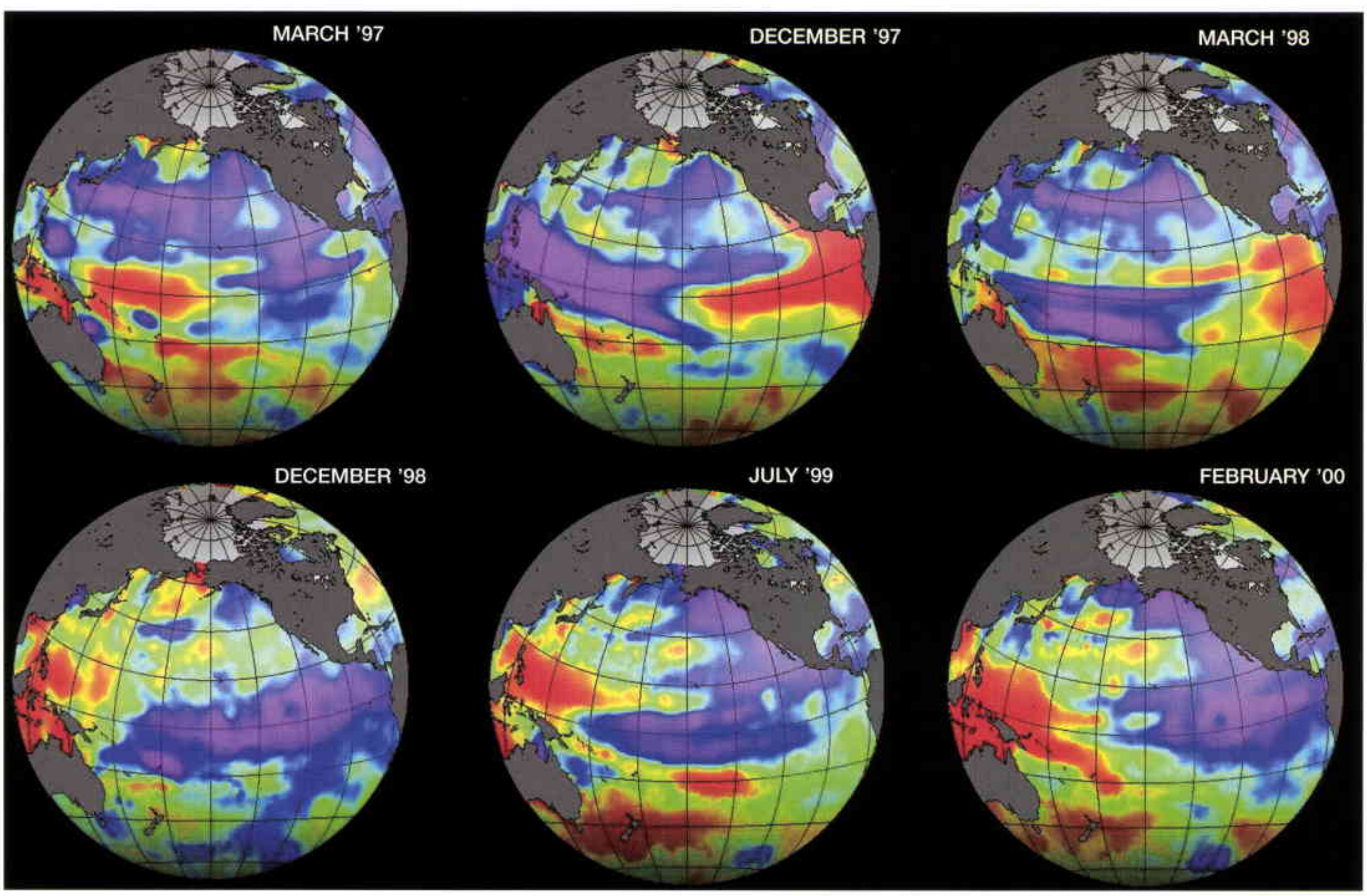


Figure 5. The El Niño/ La Niña 1997-2000 events as seen by altimetry

today's rate of global sea-level change is a crucial measurement, for which altimetry has been widely used. From their analysis of collections of tide-gauge measurements, several researchers are already quoting figures of about 1.5 mm/yr. In the framework of geodesy/altimetry, it is important to focus on how such tide-gauge and space-altimetry data can complement each other to arrive at a reliable estimation of global sea-level change. DORIS will contribute significantly in this context, providing a reliable terrestrial reference frame over time.

One crucial advantage of altimetry from space is that observations are performed on a global scale in a centre-of-mass fixed reference frame. The positions of the stations tracking the satellite define the orbit reference frame, and consequently the ability to precisely determine their locations within a co-ordinate system whose origin is located at the Earth's centre of mass is of considerable importance. It is widely agreed that the international network of satellite laser ranging systems is an important contributor to the reference-frame definition. The permanent orbitography network of DORIS beacons is the other major contributor. Indeed, since Topex/Poseidon's launch, knowledge of the co-ordinates of the ground beacons has greatly improved, allowing the DORIS system to be included in the IERS reference-frame computations.

Because a primary goal of altimetry is to contribute to a continuous ocean observing system on a long-term basis, it becomes extremely important to manage the evolution of the terrestrial reference frame. Use of the 2nd generation of DORIS instruments onboard Envisat and Jason will allow the DORIS station motion analysis to be pursued with even better accuracy, since the instrument noise of the DORIS receiver will go down to the order of 0.1 mm/s, compared with 0.3 mm/s for Topex/Poseidon-like receivers.

Another subject of careful study has to be the stability of the reference frame in which sea-levels are computed. It is known that geo-centre variations are affected by the nature of the reference system adopted, and in particular its origin. Sea-surface heights are related to the Earth's centre of mass, since the satellite orbit is defined in an inertial reference frame with that at its centre. In practice, tracking data involved in the orbit computation are collected by stations that are distributed over the Earth's surface, which contributes to the Earth-fixed reference frame definition, the so-called ITRF (International Terrestrial Reference Frame). Hence motions of the ITRF centre relative to the centre of mass should be taken into account in resolving the global mean sea-level equations.

Sea-level monitoring

Observation of the ocean is now thought of by oceanographers in terms of a global and an 'integrated' system. Indeed, there is now general acceptance that space and in-situ techniques are complementary in terms of the characteristics of their sampling, precision and accuracy, and that they must be exploited jointly to provide the optimum observing system. The same concept is valid for the sea-level-change problem, and GPS and DORIS geodetic techniques have been used for several years together with altimetry and tide-gauges data to estimate the rate of sea-level change. Continuous enhancement of the DORIS ground network by increasing the co-location of DORIS beacons with tide gauges is very attractive. Upgraded versions of the DORIS system, for instance with the multiple channel capability, now offer the possibility to design an efficient integrated tide gauge + GPS + DORIS + altimetry + laser sea-level monitoring system.

Conclusion

From its 'probationary' status on board Spot-2, the DORIS system has evolved to become a major contributor to oceanographic and geodetic science and applications. On Envisat, DORIS will contribute significantly to the fulfilment of the altimetry-mission objectives, as well as more generally supporting the instrument payload data processing, in near-real-time and off-line, with orbital information.

An International DORIS Service (IDS) is currently being created, to support the use of the DORIS system and products, to define standards, to promote research and development activities to improve system performance, operationality and applications, as well as to interact with the user community. DORIS data and expertise from the Envisat mission will be of great value for the new IDS.

Acknowledgement

We are very grateful to the DORIS programme and system teams, and particularly the DORIS/Envisat project team, for their help and their contributions to this article.

The CLARE'98 Campaign and Its Context

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CLARE'98 was the Cloud Lidar and Radar Experiment airborne and ground-based campaign carried out in October 1998. A general introduction on the wider context of this campaign and on the Earth Radiation Mission is first given, followed by a summary of the participating instruments, aircraft, institutes and the structure of the campaign. The most extensively studied flight is presented, together with some of its most relevant results. The major results and conclusions of the overall campaign are then discussed.

Introduction

The governments of most developed countries agreed at Kyoto to reduce emissions of greenhouse gases, in response to disquieting predictions of 21st century climate change resulting from human industrial and agricultural activities. Forecasts of 'global warming' range from 1 to 5 deg, with even greater discord regarding predicted regional temperatures and precipitation changes. Such predictions rely on global numerical models, and the inadequate representation of clouds and aerosols in these models constitutes a major source of uncertainty. To gain more confidence in the climate predictions and thus provide a universally agreed-upon basis for action both by governments and economic decision-makers, a first necessary step is to validate that the current weather and climate are being correctly represented.

Increases in low-level clouds cool the Earth by reflecting more sunlight, but additional high-level cold clouds warm the Earth by reducing infrared radiation losses to space. This 'cloud radiative feedback' can be larger than the original direct radiative forcing by, for example, increased CO_2. Changes in the vertical profiles of clouds lead to important changes in heating rates and atmospheric dynamics, which then feed back to cloud-profile changes. Current satellite measurements can determine incoming and outgoing radiation at the top of the atmosphere, but they cannot provide data on cloud profiles and consequent energy heating profiles. Accordingly, the Second Assessment Report of the Intergovernmental Panel on Climate Change in 1995 stated that:
'The main uncertainties in climate-model simulation arise from the difficulties in adequately representing clouds and their radiative properties'.

These uncertainties arise from shortcomings in the treatment of cloud and aerosol processes in climate models, and from the lack of observations with which to evaluate and improve these parameterisation schemes. The same difficulties bedevil numerical weather-prediction models used for short- and medium-range and seasonal forecasting. All such models divide the atmosphere into grid boxes, typically 20 – 50 km in the horizontal and 500 m in the vertical direction. Clouds are represented for each box by prognostic variables such as fractional cloud cover, ice and liquid-water content, particle size, together with some implied cloud overlap for each vertical stack of grid boxes. The overlap assumptions affect both radiative transfer and precipitation efficiency in the clouds. We have scarcely any observations with which to verify that this representation is correct. A particularly glaring gap is our ignorance of the depth and water content of the widespread tropical ice clouds.

Increases in aerosols directly modify the solar radiation reaching the ground, and also affect biochemical and photochemical processes in the atmosphere and clouds. Aerosols acting as cloud condensation nuclei also affect clouds indirectly by: (i) decreasing droplet size and so increasing cloud albedo, and (ii) increasing cloud lifetime. The indirect effect may be very strong, but in practice its impact is unknown.

The Earth Radiation Mission (ERM) addresses these issues and was one of the candidate Earth Explorer Core missions for ESA. Ultimately, ERM was not one of the two missions chosen in 1999, but ESA's Earth Sciences Advisory Committee and Earth-Observation Programme Board have recommended that a radiation mission be pursued in collaboration with Japan.

In the frame of the preparation work for the Earth Radiation Mission, several activities were carried out. Among these, an airborne and ground-based campaign was found necessary to consolidate the scientific objectives for ERM and to support the development of retrieval algorithms. Of particular interest was the development and validation of algorithms specially for the radar and lidar and mid-layer/mixed-phase clouds. A campaign (CLARA) had already been carried out in The Netherlands, but it had concentrated on ground-based measurements and airborne in-situ measurements of liquid/low-layer clouds. CLARE'98 was therefore implemented involving three instrumented aircraft and several ground-based instruments.

The ESA Earth Observation Preparatory Programme (EOPP) and the Technology Research Programme (TRP) jointly funded the campaign and the associated data analysis for retrieval-algorithm development.

The Earth Radiation Mission

The ERM is extensively described in ESA Special Publication SP-1233(3) (available from ESA Publications Division), but a brief description of its objectives and observational requirements here will allow the reader to better understand the context of the CLARE'98 campaign.

Scientific objectives

The ERM was specifically defined with the scientific objective of determining worldwide the vertical profiles of cloud and aerosol field characteristics to provide basic (and essential) input data for numerical modelling and studies (on a global scale) of:
- the divergence of radiative energy
- aerosol-cloud-radiation interaction
- the vertical distribution of water and ice and their transport by clouds
- the vertical cloud-field overlap and cloud-precipitation interactions.

These objectives were jointly defined by the Japanese and European scientific communities. The cloud and aerosol data available at present are of limited value for the validation of atmospheric models. In these models, the major uncertainty is the representation of clouds and aerosols. Traditionally, cloud parameterisation schemes in numerical models have been validated by comparing long runs of such models with the climatological observations of fluxes. Such validations are, however, rather crude, since for a given flux at the Top-of-the-Atmosphere (TOA) there is more than one possible solution. The ERM addresses this issue by using a 'snapshot approach'. This consists of measuring the vertical profiles of clouds and aerosols (using a nadir-looking radar and lidar) and the constraining TOA radiance (using a broad-band radiometer). To understand the wider context of the measurements (across-track and scene texture), an imager is used.

The mission supports the goals of the World Climate Research Programme (WCRP) and, in particular, of its Global Energy and Water Experiment (GEWEX) sub-programme, which is intended to develop an improved under-standing of energy and water fluxes within the climate system, to secure reliable forecasts of weather and climate.

In order to meet the ERM's objectives, the following observations are required on a global scale:
- cloud boundaries (top and base), even for multi-layer clouds, and consequently height-resolved fractional cloud cover
- vertical profiles of ice water content and ice particle size
- vertical profiles of liquid water content
- detection of precipitation and estimation of light precipitation
- detection of aerosol layers and estimates of their optical depth
- short-wave (SW) and long-wave (LW) radiances at the top-of-the-atmosphere.

Observational requirements

The entire set of mission observational requirements (including instrument requirements)

Table 1. Observational requirements for ERM

Parameter	Detectability	Accuracy
Fractional cloud cover	5%	5%
Cloud top/base - Ice	N/A	500 m
- Liquid	N/A	300 m
Ice water content	0.001 g m^{-3}	+40 / -30%
Ice effective radius	N/A	+40 / -30%
Liquid water content	Optical depth	+100% / -50%
(and effective radius)	1	
Aerosol optical depth	0.04	10%
SW/LW radiances, TOA	N/A	1.5 Wm^{-2} sr^{-1}

Table 2. Summary of requirements for lidar and radar

	Lidar	Radar
Footprint	≅ 100 m	< 1 km
Sensitivity	≤ 8x10^{-7} m^{-1}sr^{-1}@10 km integration ≤2.4x10^{-6} m^{-1}sr^{-1}@1 km integration	≤-36 dBZ@10 km integration ≤-31 dBZ@ 1 km integration at 8 km height
Signal-to-noise ratio	≥ 2	
Radiometric accuracy		≤ 1.7 dB
Vertical resolution	≤ 100 m	≤ 500 m
Swath	Nadir only, co-located footprints	

were driven by a TOA flux accuracy of 10 Wm^{-2} on a synoptic scale. The sensitivity limits and accuracy required for the key geophysical parameters are listed in Table 1.

The instrument complement consists of two active instruments (a radar operating at 94 GHz and a lidar at 1.06 μm) and two passive instruments (a Multi-Spectral Imager and a Broad-Band Radiometer). Table 2 shows the requirements for the key active instruments. These were also derived from the same TOA flux accuracy requirement.

As will be shown later, CLARE'98 has demonstrated that the scientific objectives can only be met with co-located and simultaneous measurements by the two active sounders with other complementary instrumentation onboard the same satellite. The radar and lidar footprints need to be co-located to better than 500 m to be able to use both active instruments in synergy to retrieve cloud properties with the required accuracy.

CLARE'98 has also demonstrated that cloud properties can be retrieved using the radar and lidar; in particular, ice water content and effective radius can only be retrieved using the two co-located and simultaneous active measurements together.

Owing to the snapshot approach used, the radar and the lidar are required to make observations in only rather narrow fields of view about nadir, with footprint dimensions of less than 200 m and 1 km, respectively.

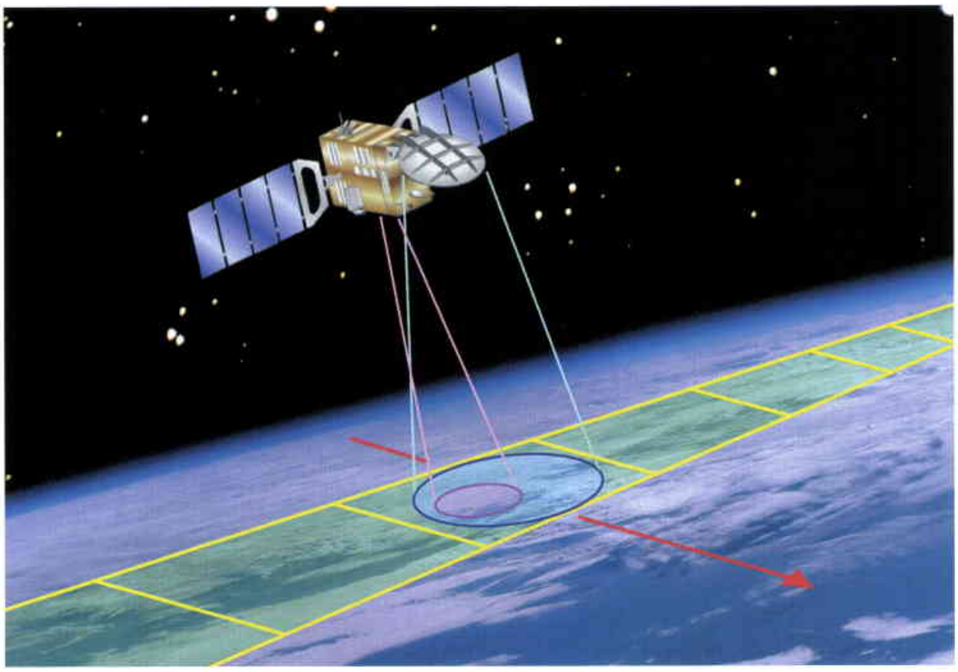
The broadband-radiometer data provides values for the radiance at the top of the atmosphere, and thus the constraining value for the estimates of the vertical radiative flux divergence profiles within the atmosphere.

The multi-spectral imager enables a clear distinction to be made between different cloud types and supplies the context in which the measurements are carried out. The passive instruments need to have larger swaths in the across-track direction than the active instruments. As the typical correlation length for cloud structures sometimes extends beyond the size of the reference cells, the swath widths of the multi-spectral imager and broadband radiometer have been specified as approximately 100 km.

Figure 1 is an artist's impression of the ERM, showing the footprints of the radar, lidar and the multi-spectral imager.

As far as the orbit requirements are concerned, a near-polar orbit ensures that all climate zones will be sampled. A polar (Sun-synchronous) orbit with an equatorial crossing time around noon will ensure a maximal signal in reflected solar radiation for both passive sensors. A preceding orbit is not strictly necessary for the ERM due to the snapshot approach used.

Figure 1. Artist's impression of the Earth Radiation Mission (ERM). The blue and lilac footprints represent the radar and the lidar, respectively. The yellow-delimited boxes depict a single row of pixels as seen by the Multi-Spectral Imager. The footprint of the Broad-Band Radiometer is not represented. The red arrow represents the ground track of the satellite at nadir



The campaign

For the purposes of CLARE'98, three aircraft were necessary. One performed *in-situ* measurements, while the other two made remote measurements from different altitudes. One of the aircraft was required to carry both a lidar and radar with characteristics similar to those proposed to be embarked on the ERM. Complementing the airborne measurements, an extensive set of ground-based measurements was also required. To take advantage of existing ground-based instrumentation and facilities, the Observatory of Chilbolton, Hampshire, UK was chosen. The campaign was carried out during the period from 5 to 23 October 1998.

Figure 2. The UKMO-MRF Hercules C-130 flying over Chilbolton (UK), where all ground-based instruments were sited. CAMRa (3 GHz scanning radar), with its 25 m antenna, and Rabelais (35 GHz radar), with its small dish on the right-hand side of the large antenna, are also shown

Aircraft

Three aircraft were used:

- A UKMO-MRF Hercules C-130, performing in-situ measurements of temperature, wind, humidity, particle-size spectra (FSSP, 2D-C and 2D-P), and bulk water (Johnson-Williams probe). In addition, this aircraft performed radiative measurements (broad-band, narrow-band plus microwave).
- A INSU/IPSL Fokker 27 (ARAT), performing measurements with a 94 GHz cloud radar ('Kestrel' from the University of Wyoming), a lidar ('Leandre') and an array of radiometers.
- A DLR Falcon, carrying out high-altitude measurements with the 'Alex' lidar and the 'Fubiss' spectrometer, as well as short- and long-wave radiometers.

The C-130 and the ARAT were present throughout the period, while the Falcon was present from 12 to 23 October. Seven flights were carried out, using the maximum flying hours allocated to this campaign.

Ground-based data were taken during the flights from radars at 3, 35 and 94/95 GHz, together with radiometers, interferometers, ceilometers, and fluxmeters. For most of these instruments, data was logged continuously throughout the campaign.

The aircraft flew runs with an azimuth of 260 deg towards and away from the Chilbolton site, where all ground-based instruments were placed (Fig. 2), each outbound or inbound flight leg being called a 'run'. The Falcon flew at a high level of about 10 km, with the lidar looking downward and generally above the cloud; the ARAT was generally at its ceiling of around 5 km with its radar and lidar looking downwards to cloud, below which the C-130 was performing in-situ micro-physical measurements. The co-ordination of the aircraft worked very well with a pair of synchronised inbound and outbound legs over Chilbolton, typically every thirty minutes. The start of the inbound run was different for each aircraft, due to their different speeds, so that the over-flight of Chilbolton occurred as much as possible at the same time for all aircraft. For the outbound runs, the latter started at Chilbolton for all aircraft. Table 3 shows the summary for the seven flights.

Ground-based instruments

The ground-based instruments were sited at the Chilbolton Observatory and consisted of:

RAL (UK)

- 3 GHz scanning (CAMRa) and 94 GHz vertically pointing radar ('Galileo', on long-term loan from ESA)
- 22, 28, 78 and 94 GHz zenith-pointing radiometers
- a UV lidar
- CT-75K Vaisala Lidar/Ceilometer (on long-term loan from ESA)
- standard meteorological instruments
- cloud camera.

CRA (F)

- 35 GHz scanning radar ('Rabelais')
- 35 GHz radiometer.

GKSS (D)

- 95 GHz vertically-pointing radar ('Miracle').

KNMI (NL)

- IR radiometers (2)
- video camera
- VIS-IR sensor.

Table 3. Summary of runs per flight

Date	Flight	C–130 runs	ARAT runs	Falcon runs
7 Oct. 1998	1	8	8	–
13 Oct. 1998	2	16	10	10
14 Oct. 1998	3	14	8	8
16 Oct. 1998	4	14	–	–
20 Oct. 1998	5	28	18	18
21 Oct. 1998	6	8	6	6
22 Oct. 1998	7	12	-	-

TU Delft/TU Eindhoven (NL)

- multi-frequency microwave radiometer (21.3, 23.8, 31.65, 51.25, 53.85 and 54.85 GHz, on loan from ESA).

Other scientists, not funded by ESA, joined the CLARE'98 campaign with their instruments on condition that the data collected would be shared. The University of Heidelberg (D) operated a high-resolution A-band radiometer, from which it should be possible to derive the optical depth and photon path-length distribution through the clouds, The University of Bath (UK) participated with GPS receivers to evaluate the path-integrated vapour and a 95 GHz high-performance radiometer, and the University of Portsmouth brought along a 40 GHz radiometer and satellite (Italsat) beacon receiver.

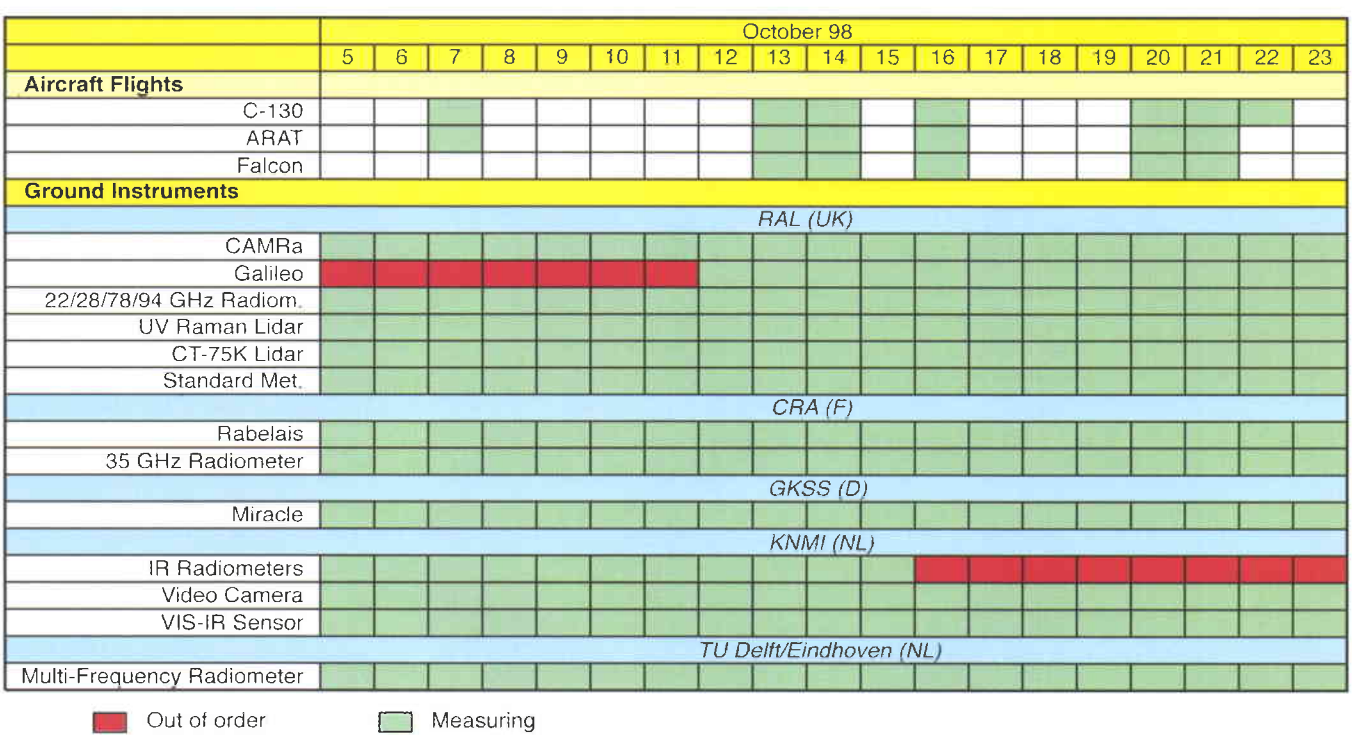
Table 4 summarises the instrument and data status for all ESA-funded instruments during the campaign.

During the flights, the scanning radars performed slow RHIs (Range Height Indicators, i.e. a scan in elevation at constant azimuth), following the aircraft as they flew along a 260 deg-azimuth line to and from the site. Figure 3 shows an example of this mode of operation, with the radar reflectivity measured by the ground-based 3 GHz radar (CAMRa), together with the lidar (ALEX) measurements performed from the Falcon and the in-situ measurements carried out by the C-130.

On other occasions, the radars performed faster RHIs to gain a greater knowledge of the overall cloud environment. At other times the scanning radars joined the other instruments in recording vertical dwells throughout the duration of the experiment.

To avoid the ground-based radars interfering with those on the ARAT, the GKSS radar had its E-field vector at 45 deg to the aircraft azimuth, and the Galileo (RAL) scanning radar had its E-field in the vertical plane.

Table 4. Summary of data availability



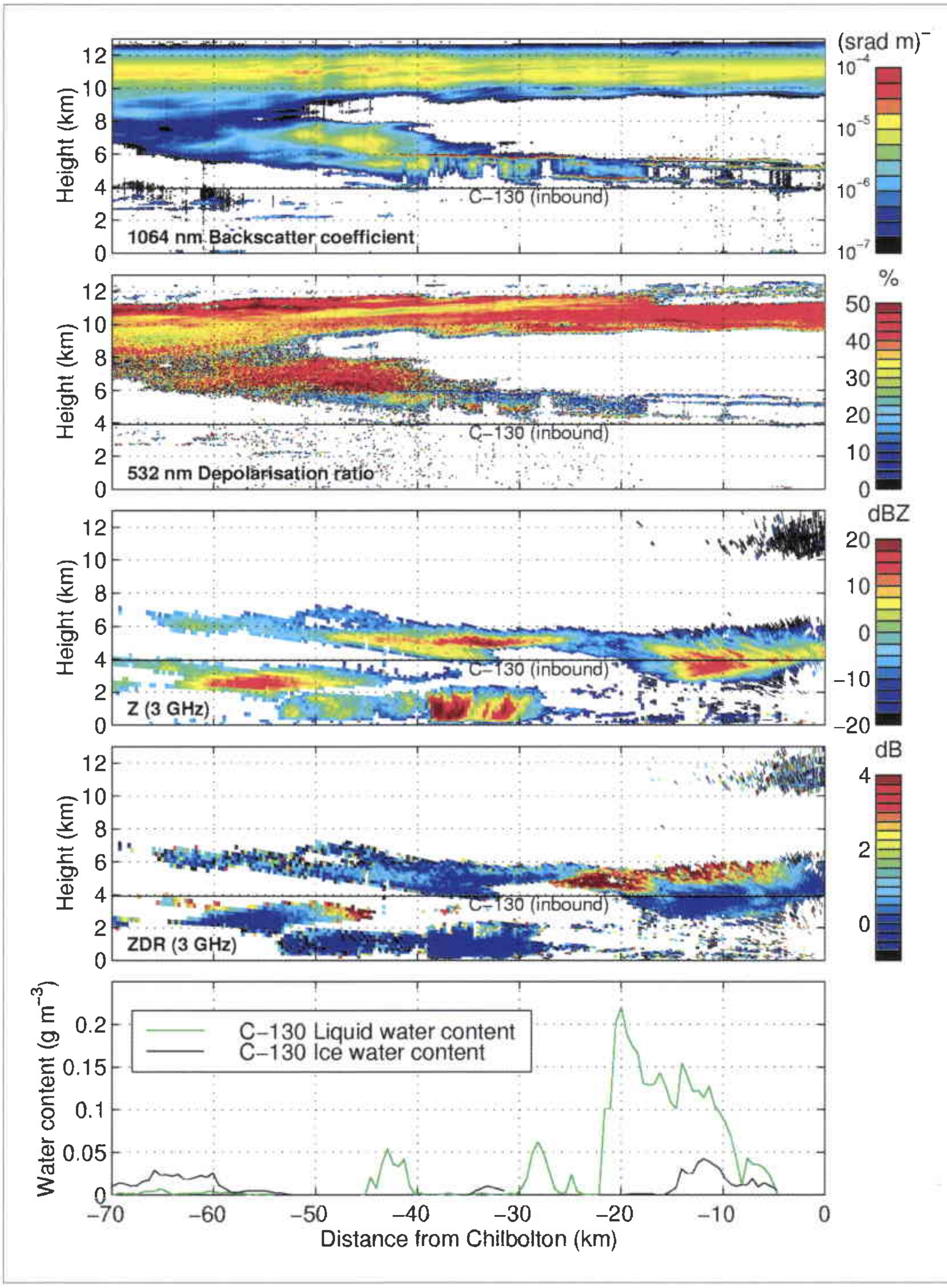


Figure 3. Composite of observations from 20 October 1998 during CLARE'98. The first two panels show measurements by the nadir-pointing lidar (ALEX) onboard the DLR Falcon aircraft flying at an altitude of 13 km. Simultaneous measurements of radar reflectivity (Z) and differential reflectivity (ZDR) by the ground-based CAMRa radar (3 GHz) at Chilbolton are shown in the next two panels. The last panel shows the liquid and ice water content measured by the C-130 aircraft at an altitude of 4 km

The fifth flight, on 20 October 1998
This has proved to be the most intensively studied flight, and therefore serves as a good example of the type of data collected and the results that can be achieved. To document the meteorological conditions, Figure 4 shows the 12:00 UTC routine meteorological (synoptic) analysis. This analysis uses the objective frontal identification of Hewson, in which the isobars are overlaid with the IR satellite data, and warm and cold fronts are shown in red and blue, respectively. Upper fronts are marked in hash shading and the broad black lines represent upper-level jets. Figure 5 shows the radiosonde 12:00 UTC ascent from Larkhill, which is 28 km west of Chilbolton.

Successful co-ordinated flights were made through ice and mixed-phase clouds ahead of advancing fronts in a strengthening south-westerly wind flow (Fig. 4). The ascent (Fig. 5) shows a saturated layer at 650 to 500 hPa. The C-130 remained airborne for 8 hours, but the other two aircraft had to return for refuelling in between. This flight has been the most intensively analysed and is the subject of a number of scientific papers.

Figure 3 shows data from the ALEX lidar looking down from the DLR Falcon for the 14:00 UTC run. The upper cirrus layer between 10 and 12 km is clearly visible, and although the ice attenuates somewhat, some highly reflecting

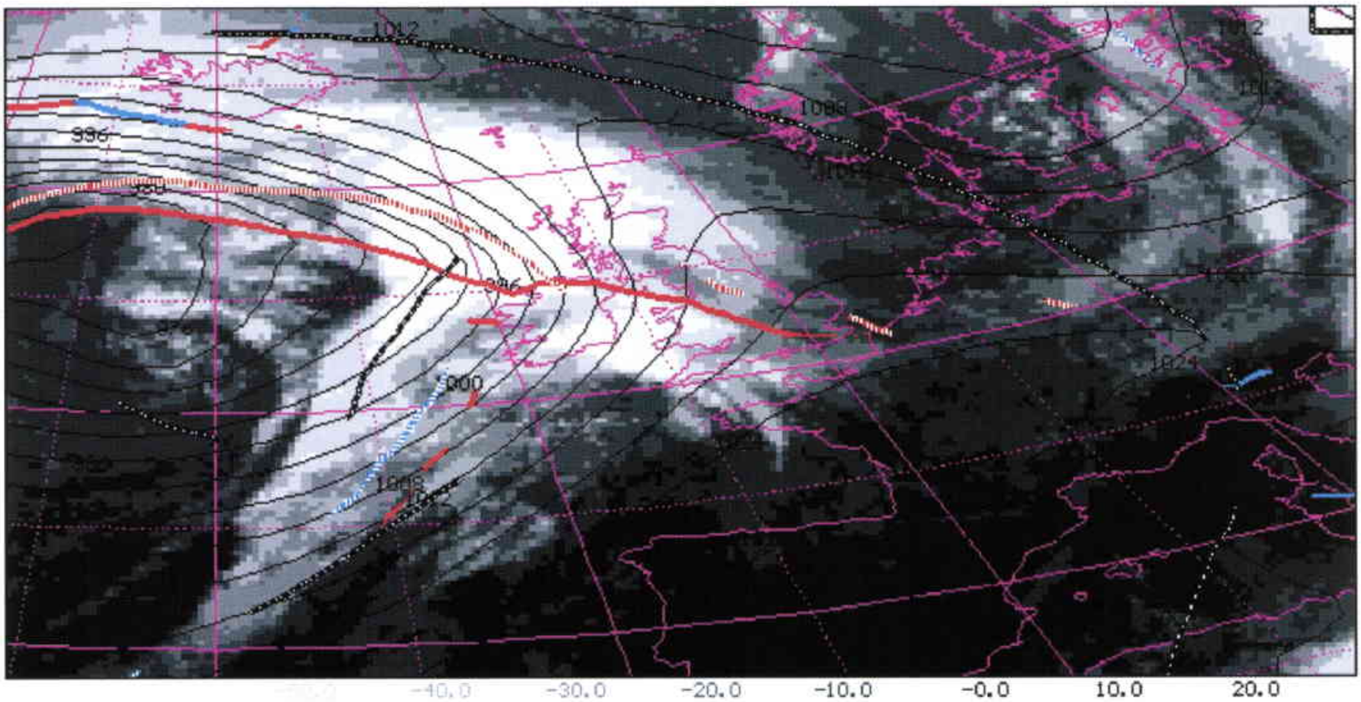


Figure 4. Synoptic situation at 12:00 UTC on 20 October 1998, from IR satellite data. Warm fronts are marked in red, cold fronts in blue, while upper-level jets are indicated by broad black lines

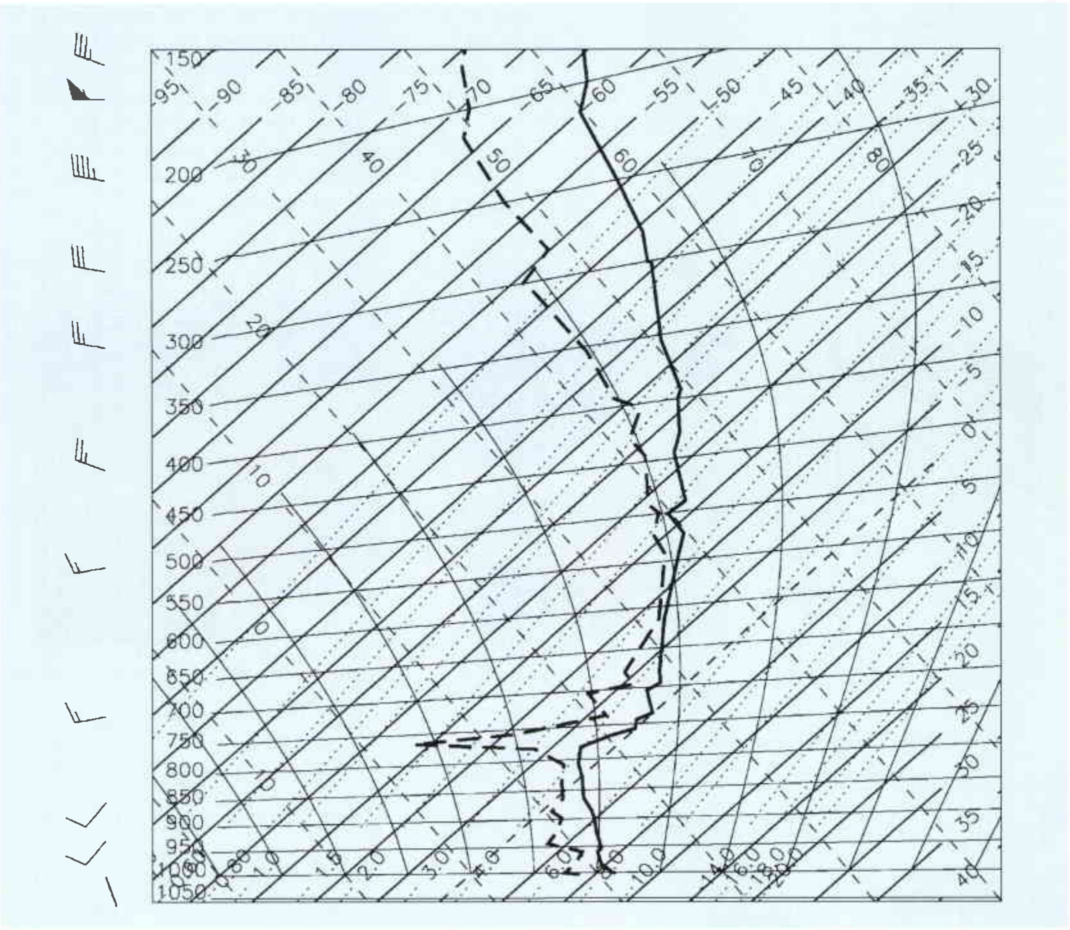


Figure 5. Radiosonde ascent at 12:00 UTC on 20 October 1998 from Larkhill (UK)

layers at a height of 4 to 6 km are evident. The first panel depicts the backscatter coefficient (β) as measured by ALEX. Thin layers of high backscatter coefficient can be seen embedded in the mid-level cloud, and the low de-polarisation of these layers as shown in the second panel indicates that they are super-cooled water. This assertion has been confirmed by other in-situ measurements carried out by the C-130. The temperature of the highest super-cooled layer is around -15°C.

The third panel shows the radar reflectivity (Z) in dBZ as measured by the ground-based scanning CAMRa (3 GHz) radar at Chilbolton, and the fourth panel the corresponding

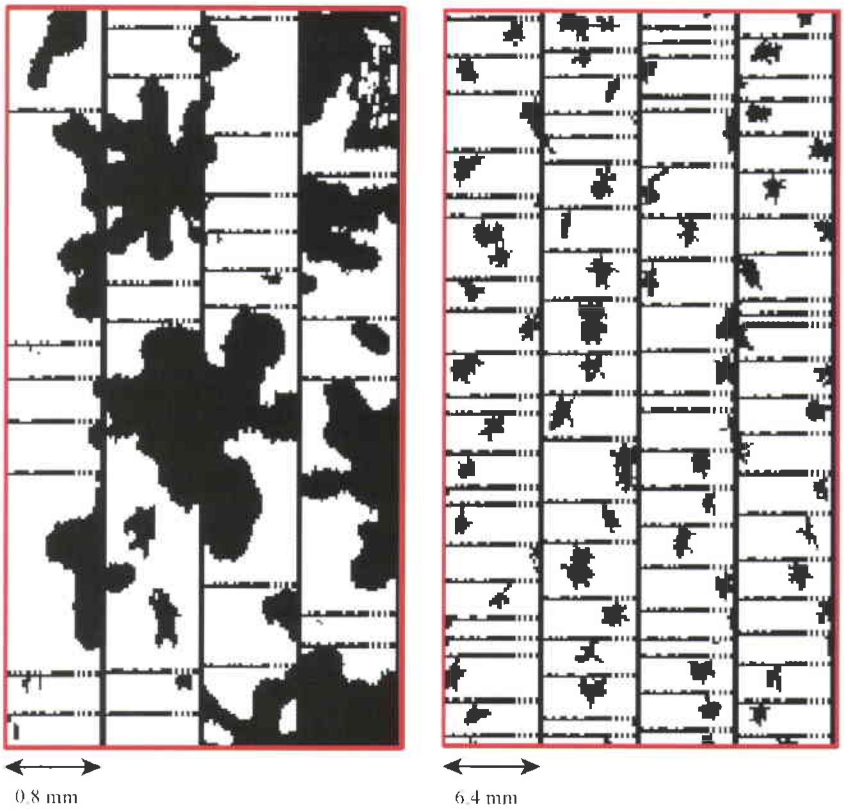
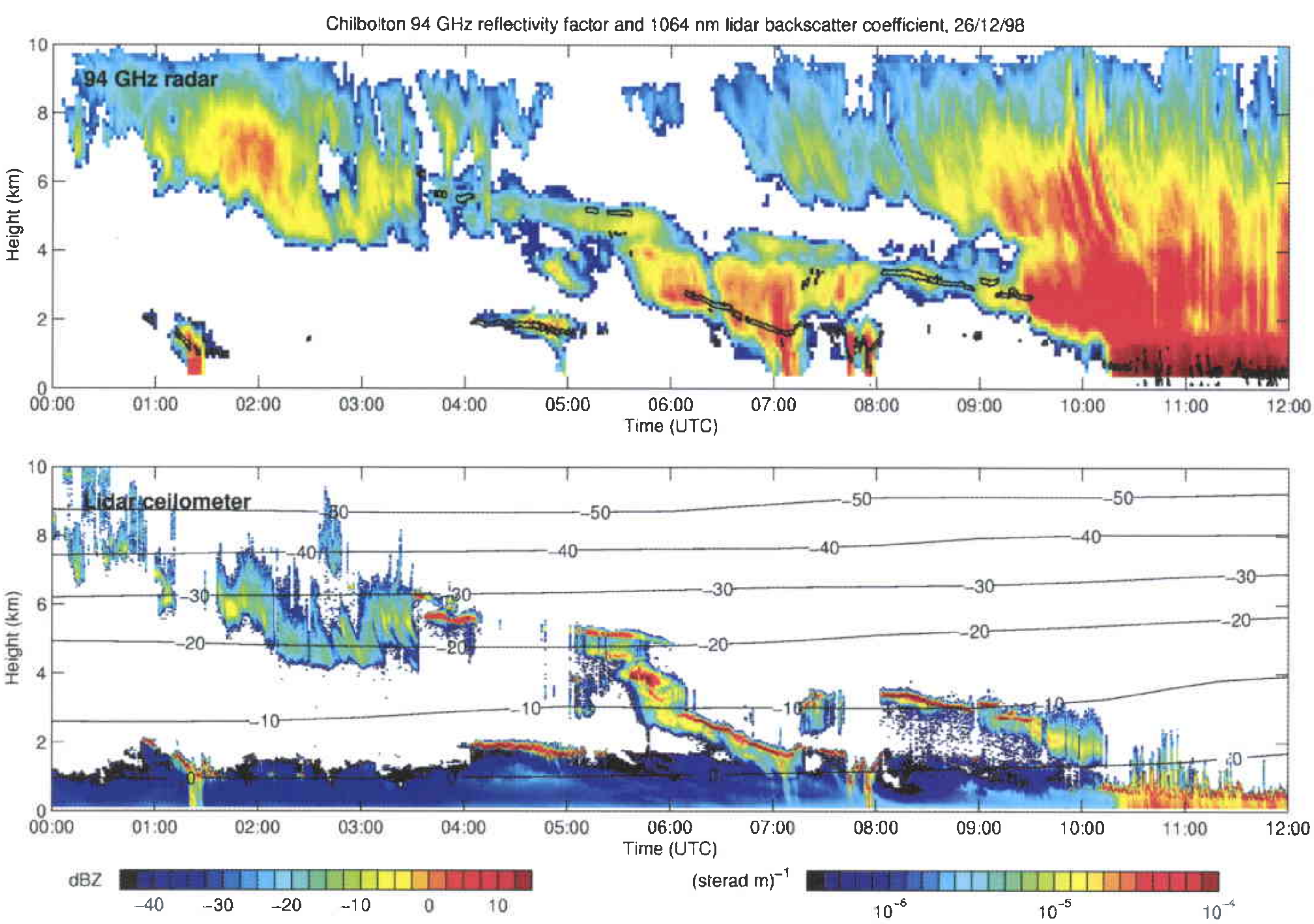


Figure 6. Data from the 2D cloud (left) and precipitation (right) probes, with the array width for each indicated

differential reflectivity (ZDR - difference between the horizontally and vertically polarised radar reflectivities). The cirrus above 9 km is largely below the sensitivity limit of the radar. In the radar-reflectivity data, there is no sign of the super-cooled layers; this is because the much larger ice crystals in the volume of cloud observed dominate the radar signal. For the later runs in this flight, these super-cooled layers have disappeared. The ZDR in the vicinity of these layers is very high, however, indicating a distinct change in ice growth behaviour. The UK Meteorological Office's C-130 was making *in-situ* micro-physical measurements at an altitude of 4 km (indicated in Fig. 3 by a continuous line in all four upper panels) where the temperature was -7°C. The last panel shows the liquid-water content

Figure 7. Continuous ground-based measurements performed by the vertically pointing Vaisala lidar and Galileo radar. The synergy between measurements shows the layers of super-cooled liquid water (marked in black in the upper panel) within the ice cloud. The upper radar plot shows a constant cloud top but a gradually descending cloud base, culminating in rain after about 10:30 UTC. The lidar signal (lower panel) shows the aerosol in the lowest kilometre and after 04:00 highly reflecting and attenuating layers of super-cooled liquid cloud droplets



(LWC) measured by the Johnson-Williams probe, and the ice-water content (IWC) measured by the 2DC and 2DP probes (see example in Fig. 6).

These measurements show that the synergetic use of radar and lidar can reveal the presence of super-cooled layers in mid-level/mixed-phase clouds. This conclusion was further confirmed by continuous ground-based observations using vertically pointing radar and lidar with characteristics similar to those that would be embarked on the ERM. Figure 7 shows an example. This type of continuous observation has also revealed that the presence of super-cooled layers in mid-level clouds is very common.

Figure 8 shows the measurements performed by Kestrel and Leandre aboard the INSU/IPSL ARAT in a subsequent run on this same flight. Using these measurements, techniques were developed and validated for retrieving the micro-physical characteristics of ice clouds. Figure 9 shows the retrieved effective radius (R_{eff}) and ice-water content (IWC).

Figure 10 shows the results of the comparison between the retrieved R_{eff} and IWC (blue lines) and those measured *in-situ* by the C-130 (red lines) that was flying at 4.6 km and under the ARAT. Figure 11 shows that the error between the retrieved and measured quantities is well within the ERM observational requirements (see Table 1, +40/-30% for both R_{eff} and IWC). In this case (Figs. 10 and 11), to ensure that the two aircraft are quasi co-located, their GPS data is used and the data are re-located to ensure that, as far as possible, the same part of the cloud is being sampled. The lowest panel of Figures 10 and 11 shows the horizontal distance between aircraft, and it can be seen that this is always less than 300 m in the area where a cloud is present.

The measurements can also be used to evaluate the co-location requirement for the radar and lidar. For this purpose, since the ARAT and C-130 have different speeds, the comparison can also be performed in terms of time. In this case, the C-130 *in-situ* data is used as a proxy for the data from one of the active instruments. Figure 12 shows the retrieved and

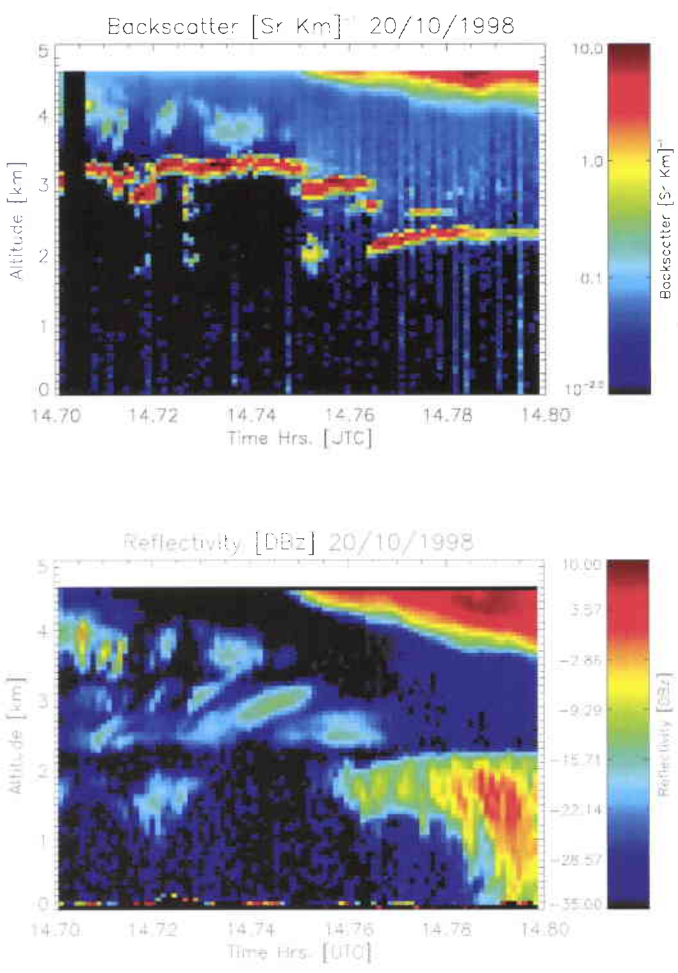


Figure 8. Measurements performed by the nadir-looking lidar (Leandre - upper panel) and radar (Kestrel - lower panel) onboard the INSU/ISPL ARAT aircraft on 20 October 1998

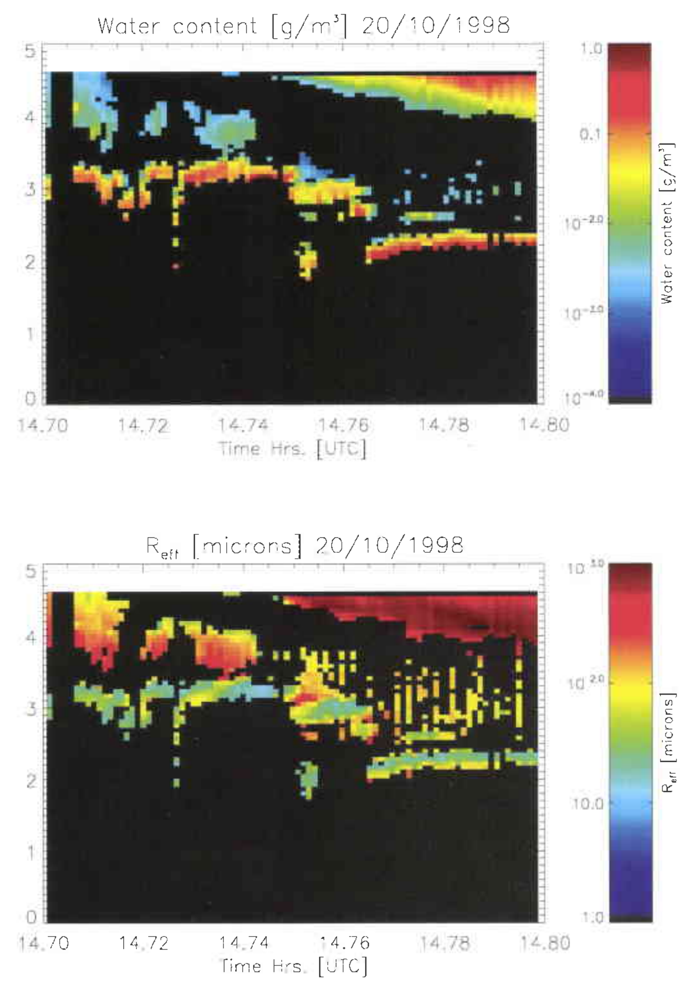


Figure 9. Ice water content (upper panel) and effective radius (lower panel) retrieved from the measurements shown in Figure 8 (after Donovan et al.)

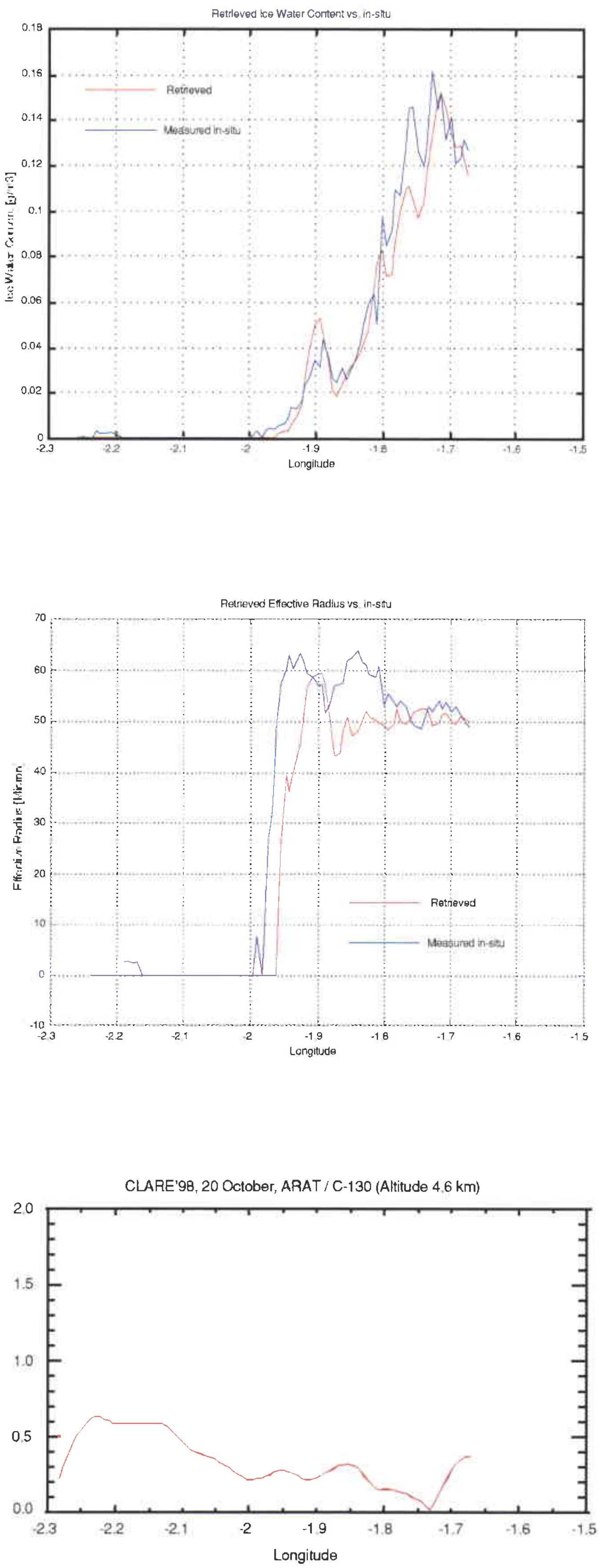


Figure 10. Measured in-situ and retrieved ice water content (first panel) and effective radius (second panel). The third panel shows the horizontal distance between aircraft

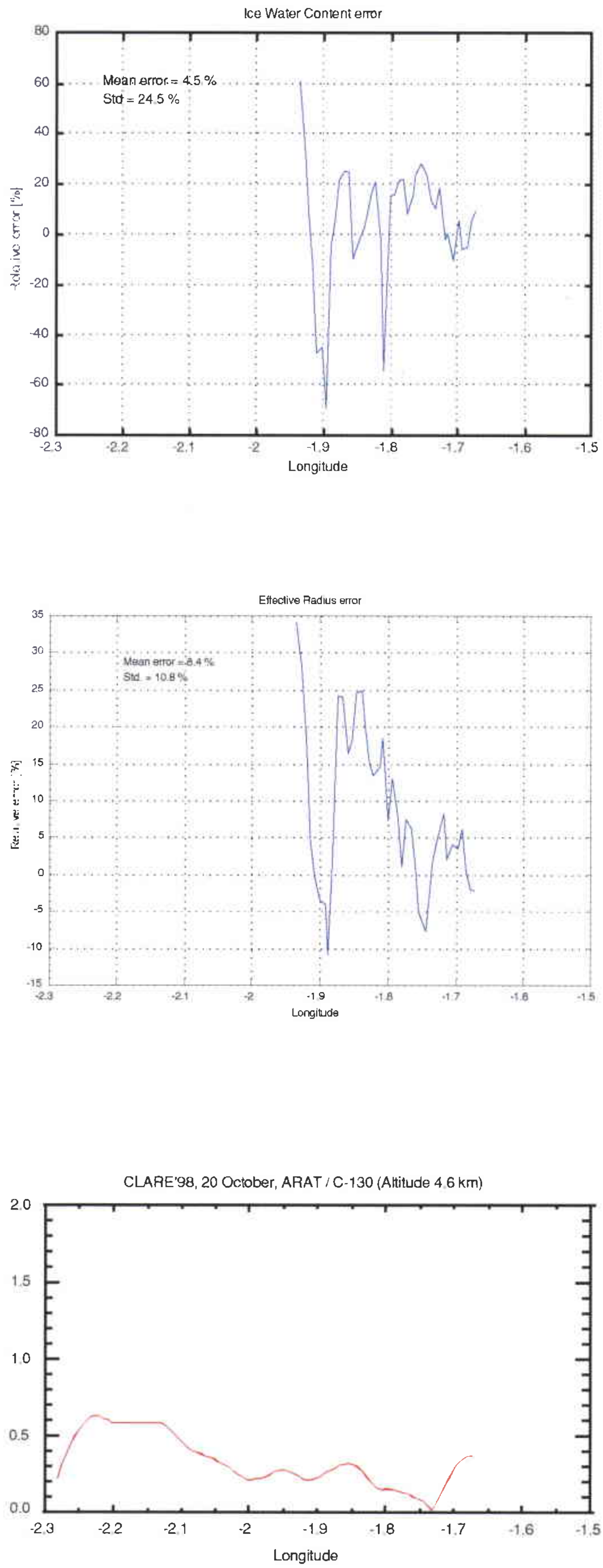


Figure 11. Relative error between measured in-situ and retrieved ice water content (first panel) and effective radius (second panel). The third panel shows the horizontal distance between aircraft

measured IWC, as well as the horizontal distance between aircraft. For a 40% error, beyond a distance of around 1 km the retrieval error is unacceptable. In any spaceborne mission, the retrieval error would be even higher due to the attenuation in the signal being simulated by the C-130 data. These results confirm the conclusions arrived at in other studies that use the spectral variability of clouds.

Major results and conclusions of CLARE'98

The major thrust of the data analysis was directed towards the validation and development of algorithms that can be used for a future space mission flying an active radar and lidar. Aspects considered are: instrument sensitivity and cloud detection, the inference of the properties of liquid, mixed phase and ice clouds, and finally the computation of radiative fluxes from the cloud properties.

Detection of clouds and cloud boundaries

The analysis performed on the data confirms that the space-borne radar and lidar proposed for the ERM should have sufficient sensitivity to detect virtually all radiatively significant ice clouds. The radar, however, would miss some thin liquid water clouds, although the lidar should see them. The instruments should detect the multi-level nature of clouds and, for ice clouds, the radar/lidar combination nearly always gave cloud bases with an accuracy of much better than 400 m (ERM requirement). We conclude that the sensitivity of the proposed space-borne instruments is adequate.

Liquid-water clouds

Vertical profiles of drop size, concentration and liquid water content can be derived from ground-based lidar, radar and radiometers on the assumption that drizzle is not present and the total droplet concentration is invariant with height. Optical depth can be derived from ground-based measurements of the oxygen A-band absorption.

These ground-based and short-range aircraft methods of remotely sensing the profiles of water content, drop size and concentrations in liquid-water content show great promise. For space-based remote sensing, a different approach will have to be used since, in liquid-water clouds, the lidar signal would be affected by multiple scattering and attenuation, while the radar would miss some of the clouds due to their very weak reflectivity and the limited radar resolution. However, the cloud boundaries (top and base) can be detected from space, and with some assumptions (e.g. vertical quasi-adiabatic behaviour) and information from passive imagers, estimates of liquid-water content can be made, but further work is needed to refine such techniques.

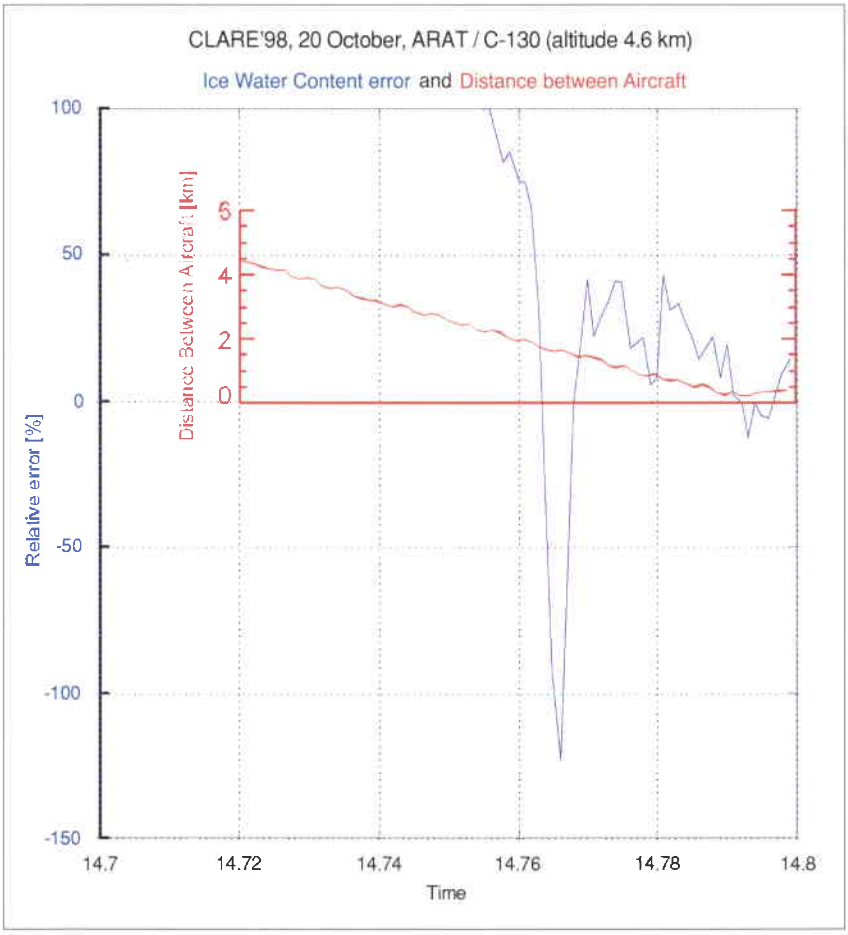


Figure 12. Relative error between measured in-situ and retrieved ice water content when the data are not co-located. The C-130 measured data are being used as a proxy for one of the active instruments. The red graph shows the horizontal distance between aircraft as a function of time. This distance decreases in the direction of Chilbolton where, in each run, the aircraft should pass overhead at the same time. As can be seen, for distances greater than 1 km the retrieval error is unacceptable for the ERM

Mixed-phase clouds

A major advance in our knowledge of mixed-phase clouds was made during the flights on 20 and 21 October, when the presence of layers of super-cooled water was clearly identified by their very high lidar backscatter, which was not accompanied by any increase in the radar reflectivity signal. These inferences were confirmed by the in-situ C-130 measurements; the C-130 aircraft penetrated the thin layer of enhanced lidar backscatter on 20 October.

Analysis of more extensive ground-based radar and lidar observations has revealed that such layers of super-cooled liquid water are quite common and can be easily identified by the combined returns of the two active instruments (Fig. 7). Clearly, the presence of such layers has important implications for the radiative properties of clouds, and also the glaciation and lifetime of cloud, which must be correctly represented in global models. The projected space-borne mission would be able to detect such layers, and this is a very important finding.

Further work is needed – requiring analysis and new observations – to perfect the algorithms for detecting such layers and to define and remove any remaining ambiguities.

Ice clouds
Our lack of quantitative global data on ice clouds is a major gap in the validation of current global-circulation models. The Earth Radiation Mission aims to fill this gap.

The combined radar and lidar should be able to detect virtually all radiatively significant ice clouds and their boundaries, as discussed above. The combined use of radar and lidar has been analysed and a stable method of correcting for lidar attenuation using the radar reflectivity as a first guess has been proposed, which then iterates to a solution for ice particle size and water content. Figures 9 and 10 show an example of the application of this new retrieval algorithm and a comparison of the retrieved Ice Water Content and Effective Radius versus the in-situ measurements. An alternative retrieval approach has also been developed based on the assumption that the normalised ice particle concentration is constant with height, and then using the combined radar and lidar to retrieve ice water content.

The analysis of the data has also demonstrated that the multiple scattering contributions from ice clouds in a space-borne lidar (as opposed to liquid clouds) should be small and should not have a major effect on the retrievals.

The CLARE'98 measurements demonstrate also that, because of the variability of ice cloud properties over short distances, the synergetic radar/lidar retrievals will only operate efficiently if the two instruments are carried on the same platform. It is concluded that the combined use of radar and lidar from space should provide unique data on such ice cloud properties as ice water content and particle size, provided both instruments are indeed embarked on the same platform.

Radiation calculations
The data analysis has demonstrated that the ground-based IR emissivity for water clouds of known temperature can be related to their liquid water path, but that for ice the relationship is less simple. The aircraft measurements show also that for water clouds, the observed radiative fluxes in the visible are consistent with the values of optical depth and albedo inferred for the cloud. As for the ground-based measurements, for ice clouds the situation is more difficult. They have many variable parameters, so that it is impossible to take the measured radiative fluxes and derive a unique cloud profile.

The approach to be adopted is the one used in the ERM. Once the profiles of ice cloud properties have been derived from the active sensors, then these values are fed into a radiative transfer model predicting the radiative fluxes. These fluxes can then be compared with the aircraft observations. It is important that this work be carried out as it parallels exactly the approach that will be used in a space-borne radiation mission.

Conclusions
As the results of CLARE'98 demonstrate, a very successful campaign consisting of seven data-collecting flights was carried out probing a variety of clouds. Associated with CLARE'98, techniques were developed and validated to derive the vertical profiles of the characteristics of liquid-water clouds from ground-based measurements. For space-based measurements, however, a different technique will have to be developed, defining cloud top and cloud base of liquid-water clouds and then using information from the passive sensors to infer cloud water content. An assumption based on the quasi-adiabatic behaviour of these clouds may further help in this development, but additional work is needed to refine such retrievals.

The synergetic use of space-borne radar and lidar should prove a powerful tool with which to quantify the occurrence of layers of super-cooled water. The representation of such layers is important in global models because of their effect on cloud radiation and cloud lifetime, but it is only with these new observations that the ubiquity of such layers in clouds has been established. Further work is needed to confirm the efficiency with which lidar and radar can identify such layers.

The synergetic use of radar and lidar is a uniquely powerful tool for quantifying the ice water content and effective radius of ice clouds, provided the two instruments are embarked on the same space-borne platform. The global characteristics of such clouds are urgently needed for validating global circulation models. Further work is needed to refine and perfect the radar and lidar retrieval algorithms.

A more powerful joint European-Japanese Earth radiation mission is being actively pursued. Such a mission would be able to address all of the key issues associated with the role of clouds and aerosols in the Earth's radiation budget.

The Ariane Charter: A Cooperative Tool to Protect and Promote the Ariane Brand Image

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The Ariane Charter and its coordinating body, the Ariane Brand Image Liaison Committee, have been in existence for ten years. At the end of 1989, ESA, CNES and Arianespace, recognising the need for stronger protection of the Ariane brand image, decided to define a joint policy. What conclusions can now be drawn from ten years of experience with the Charter's operation?

Birth of the Ariane Charter

Europe's Ariane launchers have been developed under European Space Agency programmes, with the responsibility for technical management delegated by ESA to CNES. With the formation of Arianespace, the launch-services commercialisation phase began, exploiting the various versions of the European launcher. Under an agreement between the three entities involved – ESA, CNES and Arianespace – the Ariane trademark was registered and protection obtained by CNES for France, and by ESA for other countries. Arianespace registered the Arianespace trademark and the associated logo in France and abroad.

Gradually, an Ariane brand image emerged, reflecting the prestige of the programme, the technology it represents, and European independence in space activities. All participants in the Ariane Programme have associated the Ariane brand image with their own image. The three entities also realised that other companies, not involved in the Programme, were also interested in exploiting the Ariane image to promote their own products, by incorporating it in a wide variety of media, such as films, photographs, graphics, publications and brochures. To protect the Ariane image from any form of misuse and from uncontrolled proliferation of media conveying the brand image, and to promote the image itself, the three entities therefore decided to formulate a joint policy concerning the brand image and the rules governing its use.

It was against this background that ESA, CNES and Arianespace drew up a Charter on 23 November 1989 defining a joint policy, the main points of which are as follows:

- Each party has an equal right to use the Ariane brand image for its own purposes.
- Each party must take all necessary steps to protect the Ariane image, and in particular to ensure that it has obtained all intellectual property rights and rights of use over a work conveying the image.
- Each party undertakes to keep the others informed of its promotional plans for the brand image, with a view to improving efficiency and securing effective coordination.
- Any party receiving a request for permission to use the Ariane brand image must respond in the manner appropriate to the category into which the request falls, according to the following rules:

Category A
Requests in this category are granted as of right. This category covers requests from:
a. industrial participants in the Ariane Programme
b. launch-service customers
c. scientific institutions
d. official bodies of ESA Member States
e. educational or cultural organisations.

Category B
Requests will be unconditionally rejected if they are associated with:
a. violence
b. sex
c. vulgarity
d. drugs, alcohol, tobacco, betting.

Category C
This category covers all requests that do not fall under either of the above categories.

These requests are referred to the Liaison Committee for a decision.

The Ariane Brand Image Liaison Committee

The three parties set up this Committee to coordinate actions to be taken by them under the Charter. The Committee, made up of two representatives of each party and an Executive Secretary, has the task of ensuring that the provisions of the Charter are applied. The Committee's mission is twofold: protection and promotion of the Ariane brand image.

Protection of the Ariane brand image

Every use of the Ariane image for a purpose other than providing information about space activities has to be authorised by the Committee. The main work of the Committee is therefore in dealing with Category C requests, which can be further classified into the following subcategories: industry, education, television and publicity.

For each authorised use of the Ariane brand image, the Committee informs the user of the copyright that has to be mentioned and stipulates that the authorisation is limited to the purpose and by the scope of that request. In addition, the Committee enquires into any unauthorised use of the Ariane image.

Promotion of the Ariane brand image

In the beginning, protection prevailed over promotion, due to limited resources available and a lack of coordination in the definition by parties of a joint policy on promotion. For some years now, however, the three parties, through the Committee, have been seeking to develop promotion of the Ariane brand image and to cooperate with users.

A number of companies have applied to the Committee for authorisation to use the Ariane image in the manufacture and marketing of their own products. For this purpose, the Committee has prepared licensing agreements for signature by such companies. Under these agreements, the Committee retains the right to control and supervise the quality of the products manufactured and marketed and the use made of the Ariane image.

Agreements have already been signed with several companies, including:
- ATON, which specialises in the design and production of scale models and will be bringing out a 1:400 model of Ariane-5
- Heller, which specialises in the design and production of model kits and will be making one for a 1:125 model of Ariane-5
- Sodexho, which has a large number of outlets from which it proposes to sell tee-shirts, shirts and swimwear bearing the Ariane-5 logo, and
- Laguiole, a manufacturer of high-quality knives, which will be producing and selling a knife carrying the Ariane logo.

The main industrial participants in the Ariane Programme, each having their own communication policy, are not always fully informed about the joint policy of the three entities. The Committee is now seeking to cooperate with them and will be organising workshops with them in the next few months.

Conclusions after the Committee's first ten years

The success of the Ariane Programme has strengthened the image of Ariane in the eyes of the general public. Requests to use the Ariane image continue to increase in number. The Committee is trying to encourage this trend, and to cooperate with companies applying for authorisation to use the Ariane image. Instead of simply granting or refusing authorisation, members of the Committee try to advise the applicant on the best way to promote not only the product or service for which authorisation has been requested, but also the Ariane brand image. Such cooperation plays an important part not only in the protection of the Ariane brand image, but also in its promotion. For example, some members of the Committee have worked closely with several different industries to define products to be manufactured and marketed.

The Committee sometimes learns about unauthorised use of the Ariane image by third parties. Given the success of the Ariane Programme, political parties have often used the Ariane image in their local or even national or European campaigns (Parti Républicain and recently Front National). Initially, the policy of the Committee was to refuse authorisation to political parties. A solution for the future might be to authorise all political parties to use the Ariane image, as long as they do so in accordance with the principles contained in the Charter.

The Committee has established that the brand image of Ariane is well known in France, but it is insufficiently developed in other European countries and the rest of the World (ESA Study Report on Improvement of the ESA Image, April 1999). The Committee therefore intends to work on this shortcoming.

The Kourou launch site, French Guiana

Concerning trademark and other intellectual property rights, a French court (Tribunal de Grande Instance de Paris) has recently recognised that the Ariane trademark can be described as having a 'well known' identity. Consequently, it refused a firm of undertakers the right to use the Ariane trademark, even for activities not related to space. This decision is important as it strengthened the Ariane trademark, at least in France, and may be used as a precedent in any future litigation.

There is currently no centralised management of the intellectual property rights relating to Ariane. Each entity has its own intellectual property department responsible for the registration and renewal of its respective trademarks. Each has its own policy and maintains exclusive control over litigation concerning its trademarks. The task of the Committee is to coordinate the policies of the three entities, and to maintain and update a list of all registered trademarks relevant to the Charter. The Committee has sought over the past ten years to foster discussion between representatives of the various intellectual property departments in order to define a joint policy on registration of trademarks.

With the success of the Ariane Programme, the brand image is becoming stronger, and it is the Committee's task to reinforce this trend. Vigilance has to be maintained over the multiple uses made of the Ariane brand image, but at the same time the increased interest in using it gives the Committee new opportunities, when granting authorisations, to work with the companies (participants in the Ariane Programme and others) on joint promotional efforts.

First Test Firing of an Ariane-5 Production Booster

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The first test firing of a production P230 booster for the Ariane-5 launcher was conducted successfully on 16 May 2000, on the solid-propellant-booster test stand (BEAP) in Kourou, French Guiana. The test formed part of the Ariane-5 Research and Technology Accompaniment Programme (ARTA-5)*.

Introduction

Ariane-5 accompanying activities started in 1996 with ARTA-5, based on the experience gained from Ariane-3 and 4. The objectives of this ESA programme are to monitor the performance and reliability of the Ariane-5 launcher during its operational phase, deal with ground and flight non-conformances, and assess the validity of design and material changes.

* For background information on ARTA-5, booster development and facilities, see ESA Bulletins 94 (May 1998), 69 (February 1992) and 75 (August 1993).

Figure 1. Test firing of the ARTA01 booster on 16 May 2000

The high reliability requirements set for Ariane-5 and the aim of reducing both production and operating costs have resulted in a launcher configuration that differs substantially from that of previous generations. The chosen configuration required a new solid-propellant booster. The initial development of the booster served to freeze its definition and establish the production procedures and hardware acceptance criteria. Five development and two qualification tests were performed. Presently three types of activities are being carried out under ARTA-5:
- analysis of in-flight measurements during operational launches
- recovery of flight specimens for inspection (thickness of thermal protection, nozzle parts, field joints)
- ground firings of full-scale production boosters.

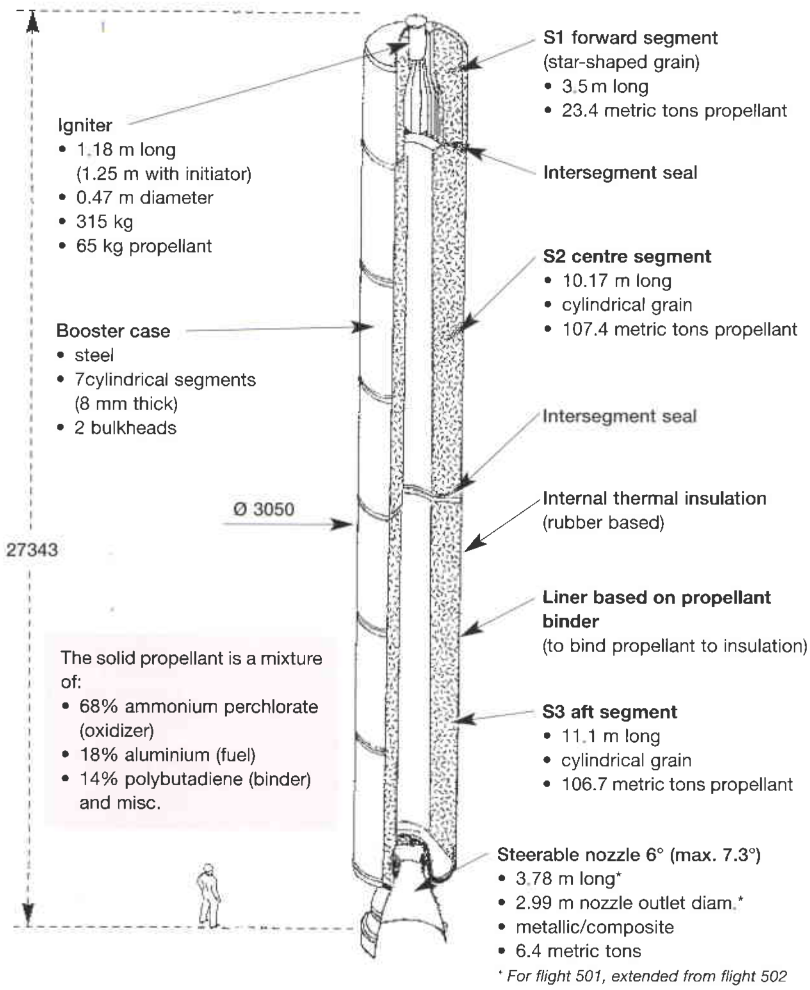
The ground test conducted on 16 May was the first firing of a production booster. CNES, on behalf of ESA, supervised all of the test-related activities. Europropulsion was responsible for the manufacture of the booster (Fig. 1).

Test objectives

The main objectives of the test were:
- verification of the performance of the motor and of the overall stage (actuators, high-pressure vessels, cable ducts, etc.)
- qualification of a new European procurement source for the binder used in the solid propellant of the middle segment (S2)
- examination of the effects of ageing on a six-year-old nozzle and evaluation of the performances of the various mechanical components
- qualification of the forward segment (S1) loaded with an extra 2.2 tons of propellant. This segment provides about 50% of total thrust during the first phase of an Ariane-5 flight. This increase, corresponding to 10% of total S1 mass, will provide an extra

payload capacity of about 200 kg for injection into Geostationary Transfer Orbit (GTO)
- validation of a new repair process developed for the thermal insulation. A repair operation was executed on a rear booster segment (S3)
- verification of the new thrust profile with the extra-loaded S1 segment and modified ignition delay, and validation of the mathematical model used to predict this profile for operational launches.

Appraisal of a set of design enhancements, basically aimed at mass reduction, was another objective. These modifications include a new attachment system for the electrical lines (now secured directly to the booster's skin by adhesive, in place of mechanical attachments) and a stretched nozzle.



Vacuum thrust		
maximum		6709 kN
average		4984 kN
Max. pressure		61.34 bar
Specific impulse		275.4 sec
Burn time		129 sec

Mass at liftoff:
inert : 31.2 metric tons
propellant: 237.7 metric tons

Total mass:
269 metric tons

Prime contractor:
EUROPROPULSION

Figure 2. Booster-motor performance characteristics

The ARTA01 motor

The Ariane-5 configuration is made up of two solid-propellant boosters attached to a cryogenic stage, the boosters providing 90% of the total propulsion at lift-off.

The P230 stage is built up from the following elements:
- solid-propellant motor (see current performance/characteristics in Fig. 2)
- nozzle control unit
- electrical and pyrotechnic subsystem
- forward and aft skirts
- forward and aft attachment devices interfacing with the cryogenic stage.

The main element is the motor, which has a metal casing in seven cylindrical sections. The casing with liner and thermal insulation is charged with three blocks of solid propellant. The nozzle has a Sepcarb throat and phenolic insulation. The igniter starts the combustion, which reaches a radial velocity of around 7.4 mm/s. The total burn time is 130 s.

For this test, the motor had the following special features:
- serial motor casing with forward segment reinforced
- thermal insulation applied using new machinery
- extra-loaded S1 forward segment
- new binder in the S2 segment
- repaired thermal insulation on the S3 segment
- new nozzle (M2R).

This nozzle is a preliminary version of the P2002 configuration due to be tested in the second test firing. Several nozzle parts have been modified, including the nose, throat and convergent inserts and the divergent. New materials have been used, namely CR 151 and Sepcarb 54-45. These modifications were driven by the need to replace obsolescent materials and optimise mass and cost.

Test-facility preparation

The BEAP test stand was built for the development of the full-scale booster and also for use during the production phase. The stand, located near the production and launch site, was designed for test-firing boosters mounted vertically, nozzle downwards, thereby reproducing flight conditions as closely as possible (Fig. 3).

The test facilities consist of the servicing tower (62 m high), the flame trench (60 m deep, 200 m long and 35 m wide), and the test control

Figure 3. The booster test stand

building located 600 m away. The main function of the tower is to hold the booster and measure the thrust during testing. The control building houses the electrical equipment and the room from which to monitor the firing.

Fifteen people were involved in the test campaign, which commenced with preparation of the stand. The mechanical and fluid systems had been dismantled on completion of the booster development and qualification phases. They were therefore reinstalled for this test firing. Initial preparation tasks on the facility took three months, from September to December 1999. The work continued from January to mid-March 2000 to achieve the final configuration required for the test. A considerable amount of instrumentation was used, requiring the installation of 429 sensors in the booster (Fig. 4).

Test results

The test was successfully performed on 16 May 2000, after a delay due to extreme weather conditions during the rainy season in French Guiana (Fig. 5).

The visual inspection after the firing (Fig. 6) was essentially devoted to the nozzle, and it confirmed:
- integrity of the divergent extremity

Figure 4. The ARTA01 booster prepared for firing

- good behaviour of the phenolic carbon of the divergent, both the currently used CR 138 and the C 151 under qualification
- a preliminary measurement of mean throat erosion of 41 mm, well within the predicted range.

The full test-result analysis is being performed in three steps:
- preliminary data analysis in the days following the tests
- Level-0 data analysis at the end of June of the whole measurement set with the help of the powerful ETNA 5+ software
- Level-1 data analysis, currently being performed together with detailed hardware inspection.

The Level-0 data analysis found good correlation between the predicted and measured combustion pressures, showing good booster performance and validating the prediction model. Final analysis at Level-1 will help to qualify the booster modifications included in this test configuration.

Conclusion

ARTA-5 accompanying activities are set to continue throughout the lifetime of the Ariane-5 launcher. The analysis of flight data combined with the sample testing for key launcher

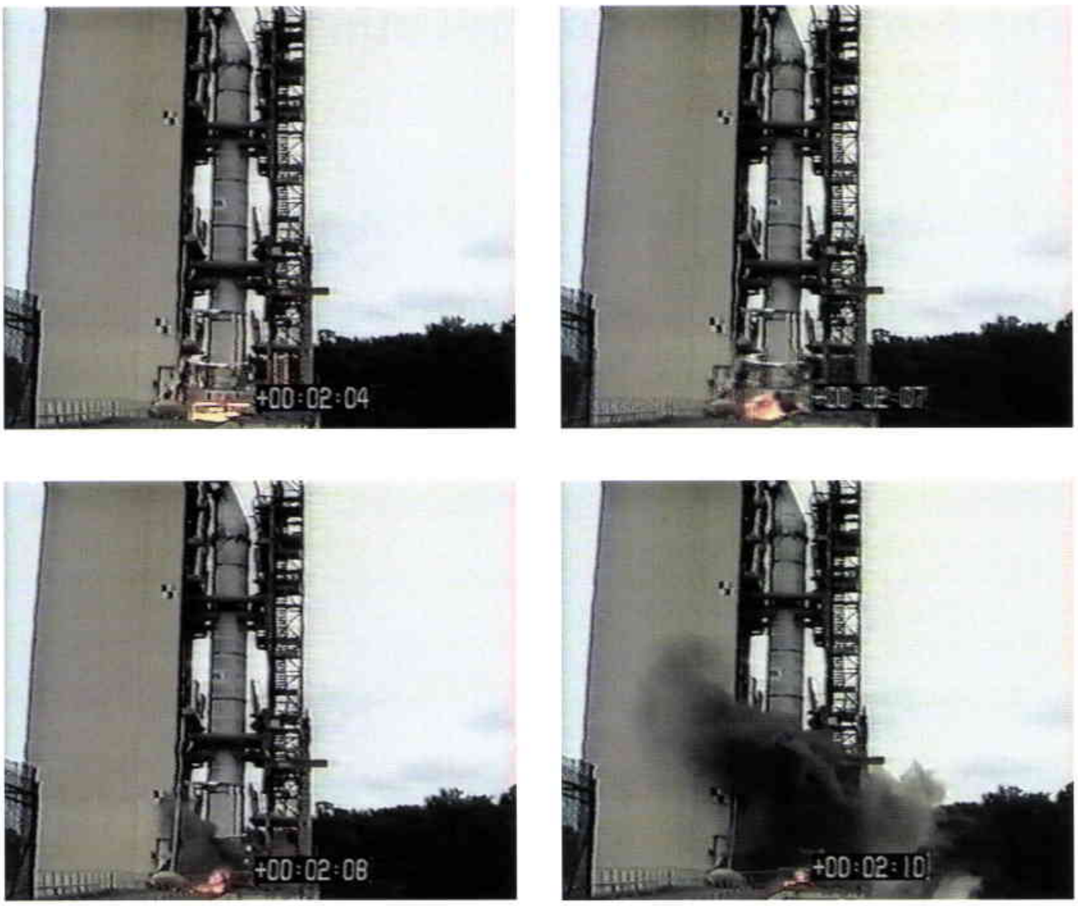


Figure 5. The booster firing sequence

elements will serve to maintain high reliability for Ariane-5. The test described here was a contribution to this objective in the solid-propulsion domain. This first test firing of an Ariane-5 production booster has shown the good functioning of the solid-rocket motor and validated proposed modifications.

Acknowledgements

The authors wish to thank CNES and Europropulsion for providing the photographs for this article.

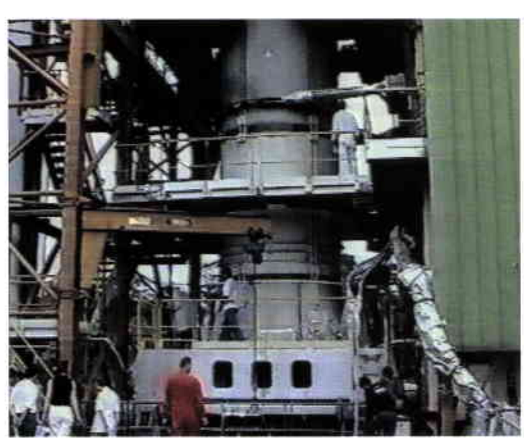


Figure 6. Post-firing booster inspection

The Future of European Launchers: The ESA Perspective

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Introduction

After an initial pioneering period in the sixties, the applications of space in the strategic and the commercial arenas, mainly in the fields of telecommunications and Earth observation, began to emerge. It therefore made sense for Europe to equip itself with independent means to guarantee its access to space. Development of the Ariane launcher was undertaken, which became a striking commercial success that far exceeded even the most optimistic forecasts. One of the main reasons for this success was the immediate focus on commercial activities.

Given that the launch-services market is undergoing a radical restructuring, Europe has to be able to offer a more complete package of services in order to maintain a sufficient level of industrial activity and reduce production costs. Therefore, for Europe to retain and improve the competitiveness of its launchers on the world stage and to satisfy evolving market demands, an optimised range of launch vehicles is needed. This immediately leads to two distinct objectives, which are: to maintain European launcher competitiveness in the short and medium term (up to 2010), and to prepare the necessary steps for the timely development of the new systems that will be required for longer term competition (2010 - 2020).

With the transformation of the Soviet Union and the changing political scenario, a totally new environment has emerged in the 1990s. As the Space Station has become an international cooperative effort, the launchers developed for military purposes in the countries that were previously part of the Soviet Union have progressively become available to the Western market for use as commercial launchers, together with a large amount of related technology. At the same time, the consolidation of the US aerospace industry has created huge corporations with strong interests in the space launcher field The satellite communications market has also evolved, with the burgeoning number of satellites required to provide the new services and the introduction of the LEO and MEO constellation concepts to serve the entire globe.

The increased competition and the newly arising markets are forcing industry towards optimised products and reduced launch prices. The greater availability of launchers is allowing the satellite manufacturers to choose and to drive launcher evolution, rather than having to adapt their designs to a few available launch vehicles.

All of these factors have totally changed the environment in which Europe had initiated the development of its own launch vehicle. One therefore has to examine the steps that now have to be taken to preserve the initial objectives of independent access to space and commercial success in the new worldwide scenario, in coherence with today's European strategic, economic and political interests.

European objectives

Modern society relies heavily on telecommunications and the associated services. This reliance has been further accentuated by the rapid emergence of information technology. It is essential not only for strategic and economic reasons, but also for political and cultural reasons, that Europe retains an independent satellite manufacturing and operating capability.

Inability to autonomously launch satellites manufactured in Europe would soon lead to the inability to preserve the satellite and space manufacturing industry, as well as restricting access to downstream application markets in the face of fully developed and organised US competition. US industry, reshaped by consolidation, is able to produce satellites and launchers within the same company, often providing the customer with a turn-key service. Europe has a growing ambition to play an active role in peacekeeping actions and disaster prevention and mitigation; this also requires a well-developed European space infrastructure for Earth observation and telecommunications, available without delay and without third-party dependency.

Preserving an independent capability for access to space is and remains therefore an essential goal for Europe. Considering the relatively limited governmental budgets available, it would appear that the objective of independence and unrestricted access may only be achievable if Europe is capable of maintaining full competitiveness on the world market. Independence must also be maintained under the condition of affordability within the European system, including governments, industry and the launch service operator, Arianespace.

Expendable-launcher activities

Launch-service providers currently competing worldwide have historically benefited from their respective governments' development of launch vehicles and the associated ground infrastructure. Such vehicles, developed for strategic reasons, have progressively become available for commercial exploitation, without requiring amortisation of the development costs. Governments also developed the launch bases and their infrastructure as part of the effort required to enter the elite of States with independent access to space.

In the last years, strong emphasis has been placed, in particular in the USA, on a drastic reduction in the cost of access to space. The sharing of work within the USA is regulated by the Presidential policy, which attributes to the Department of Defense the task of developing a new cost-effective generation of expendable launchers, through the Evolved Expendable Launch Vehicle (EELV) programme, and to NASA the task of identifying, evaluating and demonstrating the technologies required for a new generation of Reusable Launch Vehicles (RLVs).

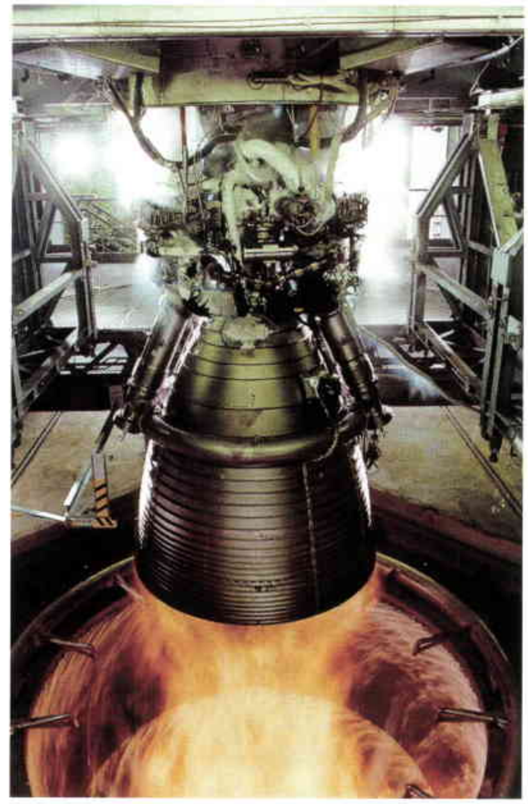
The EELV's objective is to achieve reductions in the cost of expendable launchers of the order of 25%, by making use of conventional technologies coupled with improved and simplified manufacturing processes, vehicle designs optimised for cost, and streamlined integration and launch operations. The programme is also designed to reaffirm the supremacy of the United States in the world launch-service market. The programme relies on government funding, complemented with investments by the two large US aerospace corporations, Boeing and Lockheed Martin.

The EELV programme will generate two modern families of launch vehicles, Delta-4 and Atlas-V, which in synergy with the existing smaller Delta-2, Athena, Taurus and Pegasus vehicles, will allow the USA to cover the entire range of launch services, from small to very heavy payloads, commercial and governmental missions, into LEO or towards interplanetary journeys. As part of the programme, the existing ground infrastructure will also be modernised and improved processing methods will be adopted.

An Ariane-5 launch

Ariane-5 improvements

To keep up with the above developments in the satellite market and with the growing launch-vehicle competition, ESA has proposed to European governments several improvements to the existing Ariane-5 launcher, which have been approved and are already being implemented. They will provide greater mission versatility, will increase the launcher's performance, and will also streamline production and operations, thereby reducing the specific launch cost. These improvements will be delivered by the Ariane-5 Evolution Programme, focussed on improvement of the launcher lower composite by the adoption of the larger thrust Vulcain-2 engine, and the Ariane-5 Plus Programme, focussed on improving the upper stages by adding a restart capability and the introduction of cryogenic propellants. A new upper stage cryogenic engine, Vinci, is also being developed.


The Vulcain-2 motor under test at Lampoldshausen (D)

With such improvements Ariane-5 will progressively acquire the capabilities required for dual launches into GTO of the latest and heaviest telecommunications satellites, and for the deployment in Low Earth Orbit (LEO) of satellite constellations.

In parallel, Arianespace is working with European industry to reduce manufacturing and operating costs. The streamlining of the industrial organisation, through the consolidation of European industry, is also expected to lead to cost reductions and more effective management.

The strategic goal is to serve as much as possible of the commercial GTO satellite market with multiple launches, so as to reduce the vehicle specific cost and maintain a sufficiently high production level, even in a market that, in terms of number of launches, has not grown as much as was expected a few years ago.

Complementary launchers

While these improvements will allow Ariane-5 to cope with the heaviest payloads in an economically effective manner, completion of the range of launch services offered by Europe is still a necessity, in particular through the addition of small and medium-size launchers complementing Ariane-5 for the lighter classes of payload and for Low Earth Orbit.

The diversification of the satellite market has led to a demand for launch services outside the traditional GEO orbit. Based on the history of launches conducted over the last few years, there is a clear concentration of payloads with masses of between 500 and 1500 kg being launched into LEO, corresponding essentially to governmental scientific and Earth-observation missions. Such missions, mainly sponsored by the space agencies, are aimed at the demonstration of technologies or the investigation of specific scientific phenomena with limited investments. While most of these missions demand dedicated launches into particular orbits, limitations on overall mission cost require the use of low-cost launch vehicles. Estimates made by ESA, Arianespace and industry foresee 30 – 35 missions over the next ten years from European governmental agencies in this payload class. Some of these missions will be the result of cooperative programmes and will probably fly on non-European vehicles, but more payloads will be identified from those countries that cannot rely on an independent capability for access to space.

Also considerable demand for launch services into LEO has come from the first generation of satellite constellations. The initial narrow-band constellations (i.e. Orbcomm) were composed of satellites weighing just a few hundred kilograms and used small launchers for orbit injection. The wide-band systems, such as Iridium and Globalstar, rely on satellites with masses of several hundred kilograms, which have been launched on medium-sized launchers, such as the Long March, Delta-2 and Soyuz. The next generation of broad-band systems (Skybridge, Teledesic, etc.) will rely on satellites weighing 1.5 – 2 tons, placed into higher orbits, and will require launch capabilities of 4 – 6 tons to LEO.

So it is expected that if, following the final commercial outcome of the first generation, a second generation of constellations is realised, a medium-lift launch vehicle with such capabilities to LEO will be ideally placed to serve such a market. This type of vehicle is also ideally sized for governmental missions in polar Earth orbit, as are required for civil and military Earth observation (Spot, Helios) or meteorology (Metop). The number of these missions is insufficient to justify by itself the development of a dedicated vehicle, but the use of a heavy launcher such as Ariane-5 may well involve unacceptable cost or schedule constraints.

Europe has two choices in the face of the growing demand for diversified launch services:
- to strengthen the European launcher industry by developing a coherent family of European launch vehicles, or

- to procure launch vehicles available on the market at the lowest possible cost to complement Ariane-5 in the lighter payload classes.

In the short term, the second option can be easily implemented by making use of the launch vehicles from the former Soviet Union or other non-market-economy countries, through the creation of joint ventures or direct procurement from foreign entities. While this option may be satisfactory for the customer and for the launch operator, it brings neither economic nor technical advantages to the European launcher industry.

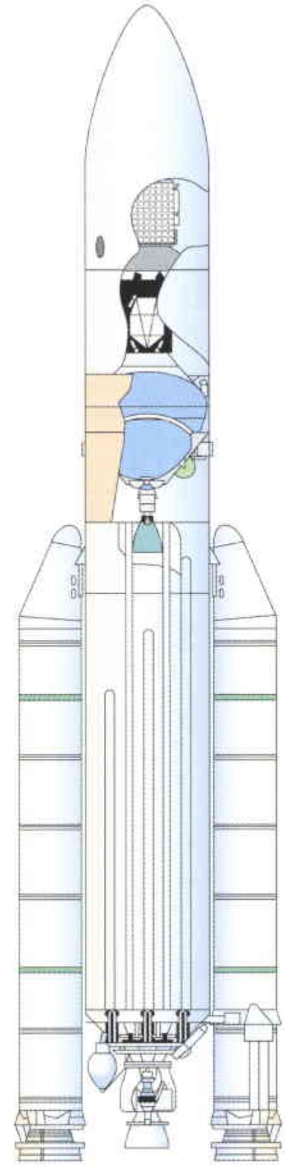
In the 1990's the European launcher industry enjoyed a favourable situation, with full production of the Ariane-4 vehicle for the commercial market in the presence of relatively weak and disorganised competition and, at the same time, was engaged in the large, government-sponsored, Ariane-5 development programme. The termination of Ariane-4 production is leading to the shutting down of several production lines all over Europe, at a time when the main Ariane-5 development effort is also being completed. The work foreseen for the Ariane-5 improvements concerns only selected areas and industry will have to rely primarily on production work and hence commercial success in the marketplace.

Artist's impression of a Vega launch

Based on market trends, 25-30 commercial GEO satellites per year are currently foreseen in the next decade, which means that Ariane-5 may be limited to a maximum of 6 to 7 commercial launches per year. This in turn may lead to under-use of the production facilities and important reductions in the industrial workforce.

To preserve Europe's independent access to space at an affordable cost, the commercial success of Ariane-5 is a pre-requisite. A key factor in this respect is the launch rate and the associated increase in production with the consequent economies of scale. Ideally for the European launcher industry, therefore, any requirement for launch services in addition to Ariane-5 should be based on the same components, use the same production facilities and launch infrastructure in Europe and French Guiana, and involve the same operational teams, in order to get maximum synergy.

As far as industrial or risk-capital investments in new launcher developments are concerned, they need to be pursued for all those activities that involve limited risk and offer a return on investment in a time interval acceptable for the financial markets. This is the case, for example, for hardware or vehicle improvements, which rely on previous developments, improvement of stages, or integration of existing elements to build up a new system. Nevertheless, government support must be provided for those activities consisting of the development of innovative technologies, new vehicles or stages, or the associated ground infrastructure, for which the risk is higher and where present world market pricing prevents the quick amortisation of the investments.

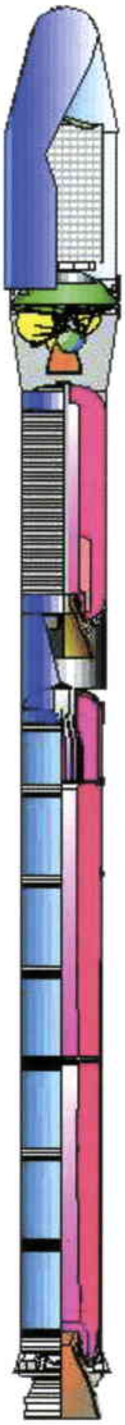


Artist's impression of Ariane-5 ESC-B

Vega

For the above reasons, ESA has proposed, following an Italian initiative, to undertake, with the participation of several of its Member States, the development of the Vega small launcher, targeting the market for small governmental missions to LEO in the payload class up to 1500 kg. This small launcher is intended to provide Europe with a low cost and flexible capability for comparatively quick access to space, on request. The production means required for such a development, and in particular those related to solid propulsion, are available from the Ariane, and other national programmes.

In the version currently under consideration, Vega consists of three solid stages (P80, Zefiro and P7), which inject the upper composite into a low-altitude elliptical orbit. A liquid upper module, known as AVUM (Attitude Control and Vernier Upper Module), is included in the upper



Possible medium-launcher configuration

composite to improve the accuracy of the primary injection (compensation of solid-propulsion performance scatter), to circularise the orbit and to perform the de-orbiting manoeuvre at the end of the mission. The AVUM also provides roll control during the final boost phases and three-axis control during ballistic phases and before payload separation. It may also be used to achieve the unconventional orbits required, for example, for some scientific missions.

The first stage, P80, will foster the development of the advanced technologies required for a new generation of solid motors with higher performance and lower cost, including a large-diameter filament-wound case for high-pressure operation, a nozzle using a new flexible joint, new thermal protections and an electric actuation system for the nozzle. This motor has replaced the initial low-cost metallic motor derived from the Ariane-5 booster, due both to its greater performance, which allows most of the small-mission requirements to be covered, including heavy radar satellites, and to the opportunity of using the Vega development to advance the solid-propulsion technology required for future improvements to Ariane-5.

The Zefiro motor, whose development was initiated by FiatAvio with company funding and a contract from the Italian Space Agency, is the second stage of Vega. It has a low-mass carbon-epoxy case, manufactured with filament-winding technology using high-strength pre-impregnated carbon fibre and a carbon phenolic nozzle with 3D carbon-carbon throat insert. Two successful motor tests have already been performed, and a third is in preparation. Currently, the propellant loading is being increased from 16 to 23 tons, by increasing the length of the motor.

The third stage is a 7-ton solid motor derived from Zefiro, but a liquid storable stage using a turbopump-fed engine was considered as a possible alternative to replace this third stage and the vernier module (AVUM). Such an engine could be derived from the current Ariane-5 upper-stage engine and would be mainly developed on the basis of industrial investments.

The Vega configurations described would use the same technologies, the same production facilities, the same operational infrastructure, the same launch pad and the same teams as the Ariane-5 launcher, thereby achieving maximum synergy and contributing to Ariane-5 cost reductions.

A European medium-size launcher

To serve the satellite-constellation market and medium-size governmental missions, a medium-size European launch vehicle may be developed, making use of elements derived from Ariane-5 and the small launcher. The market for such launcher is largely dependent on the success of the concept of constellations in LEO and MEO and, although its development is currently being studied by ESA, it will be undertaken only once the market is confirmed. Evidence as to the outcome of the first generation of constellations is expected to become available at the end of 2001.

Several configurations are presently being analysed, which are all built around existing elements, such as the Ariane-5 P230 booster, the Vega P80 motor, the Ariane-5 L10 storable upper stage with new turbopump-fed engine or new cryogenic stages (H18, H25) based on the Vinci engine, development of which is just being initiated for Ariane-5. Three possible options are P230/P80/L10, P230/H25 and P80/P80/H18. The final choice will depend essentially on the performance required and timing on the market, as Europe must not miss out on the launch opportunities provided by the second generation of constellations, if these are realised. A scenario identified by Arianespace in the event of successful development of the second generation puts the demand for constellation deployment at the equivalent of 'nine half-Ariane-5 launchers' per year.

The medium-sized launch vehicle based on the above elements will help to satisfy these market requirements, whilst simultaneously benefitting the overall Ariane system with increased production needs and synergy of operations. The development of a launcher of this class, relying largely on existing components and ground infrastructure, may be mainly funded by private investment, if the corresponding market demand is indeed confirmed.

X-33

Reusable-launcher activities

It is believed that the only potential means for further significant reduction of the recurrent launch cost is to make the launcher partially or completely reusable and to greatly increase its reliability, while preserving its operability. Reductions of one order of magnitude or more with respect to the Space Shuttle have been mentioned as the objectives of several studies and technology developments being supported by NASA and the US Air Force. In the framework of its Reusable Launch Vehicle (RLV) activities, NASA has initiated such developments as the DC-XA, X-34 and X-37 experimental vehicles, the X-33 RLV demonstrator, and many other studies and technology activities devoted to advancing the level of maturity of the critical technologies.

This trend is confirmed in the US Federal Budget request for 2001, which foresees an allocation of about 4.5 billion dollars in the period 2001–2005 for the Space Launch Initiative, covering RLV technology development and demonstration. This technology maturation phase is expected to be followed by a decision in the USA to develop a new vehicle, funded either by the government alone or jointly by government and industry.

A major driver for the USA in developing an RLV is the need to replace the ageing Space Shuttle fleet. The Shuttle, with its large cargo capability, will be the main player in the construction and operation of the International Space Station, but its high operation and maintenance costs and the need for major vehicle refurbishment lead NASA to envisage a decision on the development of a second-generation reusable transportation system by 2005. Trade-offs of various solutions are currently being performed, with a view to producing an operational vehicle by 2012.

The US military could decide, more or less at the same time, to develop a sub-orbital or orbital, global-reach space plane to satisfy military mission requirements. This interest is confirmed by a number of developments sponsored by the US Air Force, such as the initial DC-X vehicle, the X-40A and the military participation in the NASA X-37 financing. Such a global-reach space plane would be government funded and would not be available for commercial applications, although there would be the technology return to industry.

In parallel, there are a number of private initiatives aimed at developing orbital or sub-orbital reusable vehicles for the smaller payload classes. Some of them have gained official support under the NASA programmes and one or more of these proposed concepts might receive sufficient funds to provide a reusable or semi-reusable small launcher. Demonstrations of air breathing high-speed propulsion systems are also being pursued in the USA and around 2005 these systems could be considered for the initial development of long-range, high-speed military applications.

Although it is not clear that the anticipated large cost reductions can indeed be achieved in the short or medium term, these on-going developments in the USA will allow a better understanding of the critical areas, the development of new technologies and the operation in flight of several experimental vehicles. In the longer term (2015 – 2020), therefore, Europe cannot be sure of maintaining its market share by the use of conventional expendable launchers, if a technical break-through is achieved elsewhere. Such step may initially result from the need to satisfy US national requirements, but it could also heavily affect the worldwide commercial launch service scenario.

The FLTP programme

Back in 1994, ESA proposed the Future European Space Transportation Investigations Programme (FESTIP) to its Member States, in order to study possible RLV concepts and initiate the development of the related technologies. Several launcher concepts were subsequently designed

X-37

NASA X-vehicles

X-34

at a sufficient level of detail to perform comparisons and evaluations of the technological developments required, and the associated development and launch-service costs were also assessed. In parallel, a number of critical technical problems were analysed and hardware developments aimed at demonstrating possible solutions were performed.

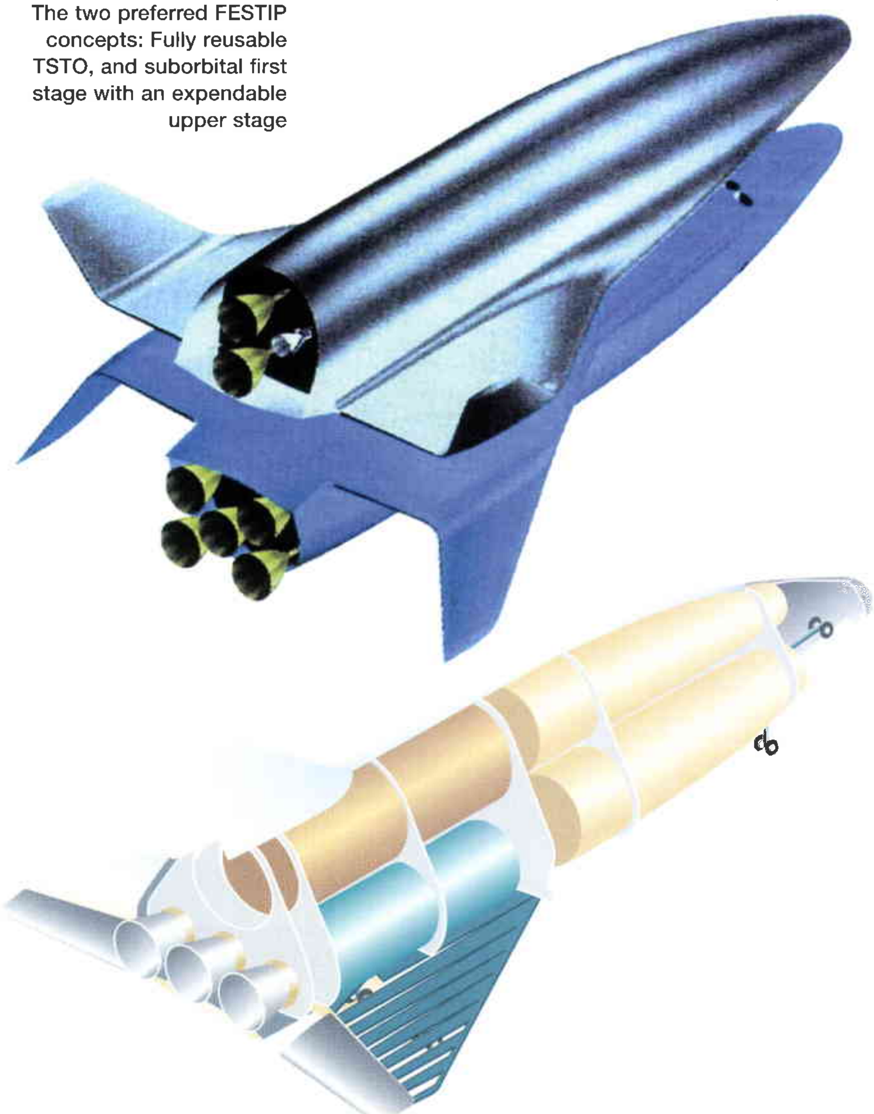
To further its understanding of launcher reusability, already investigated in FESTIP and other national programmes, and to improve the related European technology level, ESA proposed a new optional programme to its Member States in 1999, namely the Future Launchers Technologies Programme (FLTP), the primary objectives of which are:
- to confirm the interest of launcher reusability
- to identify, develop and validate the technologies required to make possible the development of a new generation of cost effective launchers
- to elaborate a plan for the ground and in-flight experimentation and demonstrations required to achieve a sufficient level of confidence prior to the vehicle development phase and to progressively implement such demonstrations
- to provide, through the analysis of candidate vehicle concepts and the synthesis of the technology activities, elements in support of a possible programmatic decision on the initiation of a European development programme for the next generation of launchers, which is currently not expected to be required before 2007.

The technology developments represent the largest part of the activities in the first period of the FLTP (1999–2001). In particular, strong emphasis is placed on propulsion, large launcher structures and reusability aspects (e.g. health monitoring, inspections).

The vehicle concept definition work is aimed at the definition of reference architectures and system concepts for future commercial operational vehicles. It deals more specifically with:
- the selection of dimensioning missions and the pre-design of a limited number of baseline configurations
- the identification of the technology requirements that must be met to make the concepts feasible
- the overall system architecture optimisation, with emphasis on operability and on re-usability assessment
- the performance of cost assessments, including technology development costs, launcher development costs and recurrent operating costs
- the technology-readiness assessment and the definition of the programmatic features for a potential future launcher development.

A large number of candidate concepts have been studied since the early eighties within the framework of the ESA activities and in national programmes. Recently, the ESA FESTIP programme made a systematic effort to compare reusable and partially reusable launcher concepts against common defined requirements and on the basis of common design rules. All of this work will serve as an input to the FLTP. Candidate concepts include both fully reusable and semi-reusable launchers.

Semi-reusable concepts, whether Two-Stage-To-Orbit (TSTO), or multiple stage to orbit, can be considered as technically feasible with the present technology. Moreover, they can be viewed as a step towards the development of more advanced fully reusable concepts. Such concepts have been studied on several occasions in Europe. So far, the conclusion has been that the specific recurrent costs achieved



The two preferred FESTIP concepts: Fully reusable TSTO, and suborbital first stage with an expendable upper stage

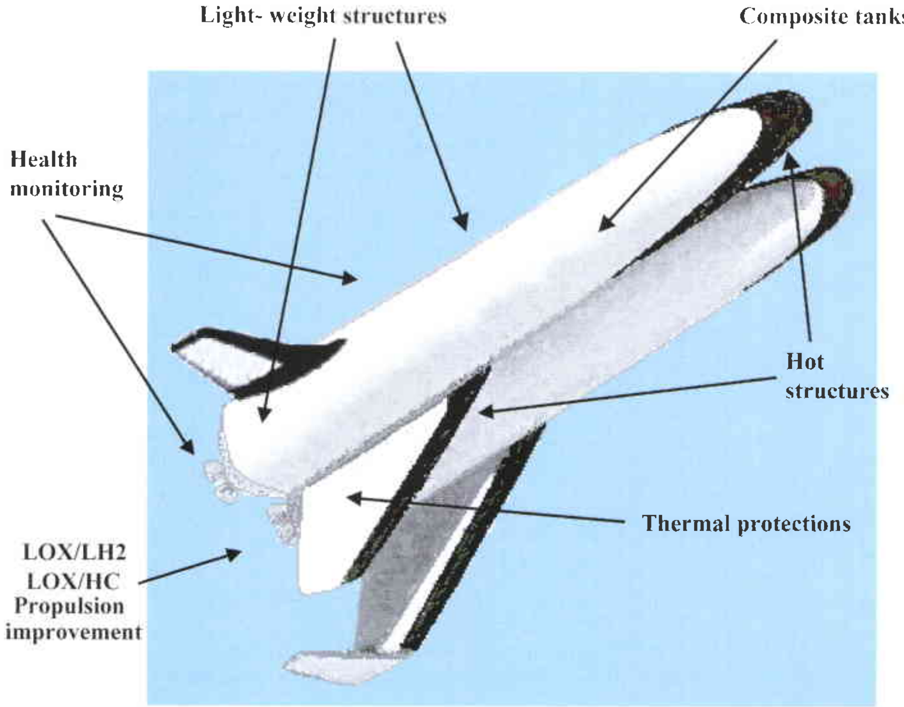
are of the same order as those of today's Ariane-5 (for a higher launcher complexity). The competitiveness of these particular concepts is therefore difficult to demonstrate with respect to the ELVs expected to be available in 15 years from now, and even more so if the USA offers a fully Reusable Launch Vehicle (RLV) on the market. However, all of the possibilities for semi-reusable launchers have not yet been exhausted, which is why the work on such concepts is being pursued within the FLTP.

A particular type of semi-reusable launcher is the sub-orbital launcher, which requires somewhat more advanced technology, but still seems to be within reach. This vehicle does not achieve a stable orbit, so that its payload needs an additional boost to reach orbital velocity, to be provided by an expendable upper stage. The concept is technically promising, but its largest uncertainties are associated with its innovative operation cycle, which includes a downrange landing. Further studies should provide the elements needed to finally assess the feasibility and cost effectiveness of the concept.

Several fully reusable launcher concepts – both Single-Stage-To-Orbit (SSTO) and Two-Stage-To-Orbit (TSTO) – have been proposed worldwide. Some have even progressed towards the development phase. The TSTO family of fully reusable concepts appears to be feasible with the least technology innovation. Further concept trade-offs are required, in particular related to the return of the first stage to the launch base. Progress in propulsion technology may be required if the size of the vehicle is not to become excessive.

The rocket-propelled SSTO reusable launcher constitutes a large step in terms of the technology level required. This option was the goal of the work performed in the USA by Lockheed Martin. So far, the concept studies have shown a high potential for recurring-cost reductions, but with large uncertainties due, in particular, to the high sensitivity of the design to technological assumptions. Even for the USA, the technical difficulties and operational implications of realising an SSTO launcher are considerable and may not be resolved soon.

The reusable launcher concepts using advanced air-breathing propulsion, either in the form of a ramjet, supersonic combustion ramjet or air liquefaction, separation and collection techniques, require technologies that are very far from implementation on operational vehicles. This type of vehicle might be of interest for later generations of RLVs, which aim at a further significant reduction of recurrent costs. They are presently seen in Europe as a subject for long-term research. Initial applications for some of these types of propulsion (ramjet, scramjet) will be in the field of high-speed military craft.



FLTP technology demonstrators

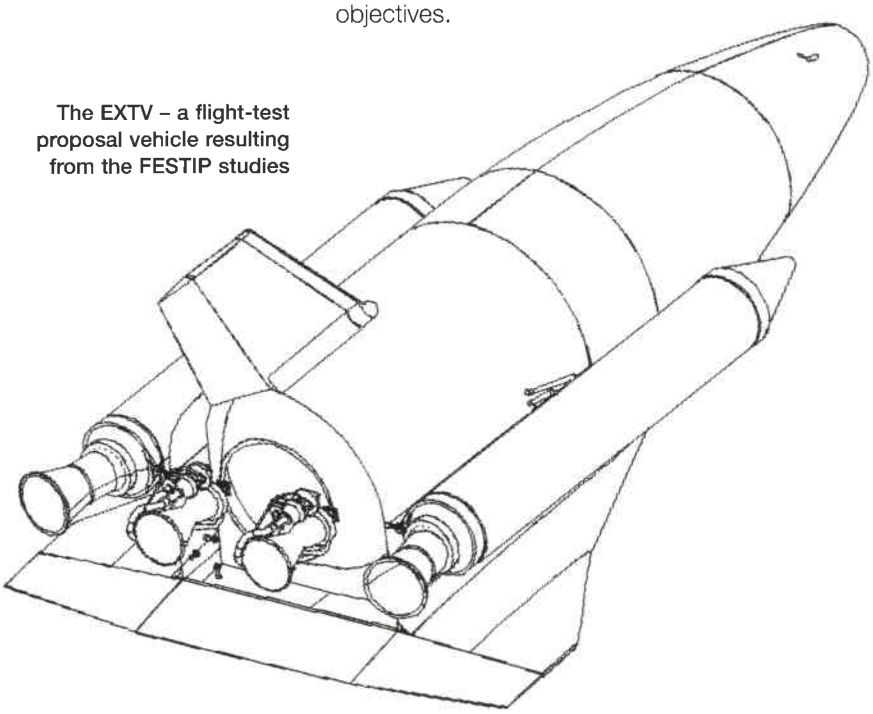
The FLTP technology-development and on-ground demonstration activities include:
- rocket-engine cycle analyses and definition of requirements for reusability
- propulsion component development and testing
- demonstration of lightweight reusable structures (cryogenic tanks, primary structures, thermal protection and hot structures)
- health-monitoring systems for structures and propulsion systems
- analysis and verification of critical aero-thermodynamic phenomena.

Rocket propulsion has advanced significantly through the Ariane programmes, which, in particular, have allowed Europe to gain experience with the operation of cryogenic engines. For new launcher concepts, further advances are required in order to introduce engine reusability and operability, to increase the level of performance and thrust. For example, fully reusable vehicles will benefit from higher-thrust cryogenic engines than those available in Europe today.

For these rocket engines, new components need to be developed, such as advanced nozzles, new types of injectors, simplified and more robust turbo machinery, electrically actuated precision valves, etc. Preliminary demonstration of these components is essential.

For reusable engines, reliability in flight and rapid maintenance on the ground are essential aspects. This means that a completely new design approach is required, which greatly reduces the need for acceptance testing, relies on an integrated health-monitoring system, and makes it possible to control or limit the effects of failures.

Launcher cost reduction and performance improvement also rely on advanced materials, manufacturing processes and improved structural concepts, which allow lower operating costs, reduced vehicle dry masses, as well as reliable, maintainable and health-monitored structures. As a design goal, the structures must have the lowest possible masses compatible with the combined mechanical, thermal and fatigue load, reusability and cost objectives.



The EXTV – a flight-test proposal vehicle resulting from the FESTIP studies

Europe has acquired experience in the manufacturing of metallic and composite expendable structures. Optimisation of design with regard to non-conventional reusable structural concepts and investigation of material characteristics associated with reusability (cyclic loading, environmental resistance, long-term compatibility with propellants, fatigue, operational life including reentry, repair techniques and non-destructive inspection) will induce structural ratio improvements that can only be verified by representative vehicle structure demonstrations.

Therefore within FLTP it is planned to design, manufacture and test:
- a low-mass, reusable composite cryogenic tank
- a light metallic (aluminium-lithium) cryogenic tank
- large airframe elements (inter-tank structure, thrust frame) with integrated health-monitoring systems
- metallic and non-metallic thermal-protection systems improved with respect to mass, reusability and operational constraints
- highly loaded hot structural elements such as wing leading edges, flaps and rudders, using metallic or composite (C/C and C/SiC) materials
- new health-monitoring and non-destructive-inspection techniques.

Aerothermodynamics is also a key technology for reusable launchers, providing the necessary inputs to all other major technologies such as flight mechanics or structures and thermal protection.

Roughly ten years ago with the Hermes programme, a vast wealth of know-how and capabilities was generated in Europe. Similar achievements were acquired in national programmes such as Sänger or PREPHA, which have partly been advanced in FESTIP. At the same time, a number of large test facilities have been built throughout Europe, allowing a substantial extension of the possible test domains.

In order to preserve and improve the available European hypersonic know-how, in FLTP work will be performed on a limited number of basic aerothermodynamic launcher problems (e.g. base drag, effect of multiple propulsion plumes, shock-wave/boundary-layer interaction, laminar/turbulent transition, etc.), which are critical for the practical design of reusable launchers.

However, the area in which Europe needs to make major progress is that of in-flight experimentation. Many of the phenomena influencing the mission of a reusable launcher cannot be reproduced on the ground, and in-flight experimentation is the only means of verifying the theoretical predictions and reducing the technological risk, before starting full-scale vehicle development. Today Europe has no direct experience with high-speed flight and atmospheric reentry by large winged vehicles. Moreover, the shape of these vehicles is often driven by the high-speed flight qualities, resulting in poor low-speed aerodynamics, which makes it difficult to perform low-speed manoeuvres and automatic landings. No experience with the reusability of materials, structures and repeated operation of propulsion systems is available.

For similar reasons, great emphasis has been placed in the USA since the 60's on the design, manufacture and testing of dedicated experimental vehicles, which paved the way for the Space Shuttle's development. The Shuttle in turn is today providing a large amount of flight data, which the USA can use to design a second generation of reusable launch vehicles. Nevertheless, as mentioned above, several additional X-vehicles are currently being developed or are planned by NASA to gain additional operational experience in the various aspects of reusable launcher missions.

In Europe, atmospheric re-entry experience has been gained with ESA's Atmospheric Reentry Demonstrator (ARD) and other capsules developed at national level and in military activities. But none of these vehicles was reusable, nor had a shape comparable to a reusable launcher.

Within the FESTIP programme, ESA has pursued flight opportunities for passenger experiments on 'foreign' vehicles. For example, an agreement has been concluded with NASA which will allow repeated flights on the X-34 vehicle of two European thermal-protection systems.

In parallel, in the framework of the International Space Station activities, Europe is participating in the development of the X-38 and CRV vehicles, which with their demonstration flights will offer an additional opportunity for testing European elements under reentry conditions.

The preparation of a coherent flight experimentation approach is an essential part of the FLTP. The requisite flight activities will be defined at an early phase in the FLTP on the basis of the needs identified, including cost evaluation of the corresponding hardware development and testing. In-flight experiments will be progressively implemented according to the level of technological maturity achieved and the available flight opportunities.

Part of the overall FLTP in-flight experimentation activities will be:
- elaboration of a flight experimentation strategy
- definition of in-flight experiments as passengers on existing vehicles, including opportunities for international co-operation
- development and testing of flying testbeds focussing on the validation of specific technologies and operational aspects required for future European launchers
- elaboration of a technical and programmatic proposal for the development of the experimental vehicles required for mastering the various phases of the reusable launcher mission
- design, development and in-flight testing of selected experimental vehicles.

The definition of flight passenger experiments and testbeds will be initiated in the first phase of the programme. However, the major emphasis in this phase will be on the elaboration of proposals for experimental vehicles, to be implemented in the programme continuation.

The decision to actually develop a reusable launcher will largely depend on the evolution of the international market and competition. Since the Space Shuttle will remain in service until about 2012, a US RLV development decision is planned around 2005.

In formulating its own strategy, Europe will have to consider both autonomous developments as well as international cooperation, in order to advance its technology level. In particular, it should be taken into account that the first RLV in the USA may be developed for the governmental missions to the International Space Station and preparation of a space exploration infrastructure. Europe may be called upon to participate in some aspects of such development. Commercial vehicles will represent a later spin-off of the government-funded developments. Europe must therefore consider carefully what are the most effective steps for reducing the vehicle development risk to acceptable levels before possibly committing to its own RLV development effort around 2006 – 2007.

Conclusion

On the basis of the anticipated world-wide launch-service scenario outlined above and the already defined European objectives, three lines of action should be pursued:
- to maintain Ariane-5's competitiveness in the short and medium term, by improvements to the launcher (greater mission versatility, increased launcher performance, optimisation of production and operations) aimed at reducing specific launch cost
- to complete the range of launch services offered by the possible addition of European-manufactured small- and medium-sized launchers, in order to compete effectively on the international market
- to prepare the technology needed for the timely development of the new systems that may be required in the longer term (2015 – 2020).

These three steps will together allow Europe to retain its current leading position in the launch market and maintain its independent access to space, which is crucial for any future strategic space activity.

Solar Orbiter: A Challenging Mission Design for Near-Sun Observations

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The Sun's atmosphere and heliosphere represent uniquely accessible domains of space, where fundamental physical processes common to solar, astrophysical and laboratory plasmas can be studied under conditions impossible to duplicate on Earth, and at a level of detail that it is not possible to achieve at astronomical distances. A Solar Orbiter Mission designed to take the next step in our exploration of these domains was the topic of a technical pre-assessment study performed in 1999 within the framework of ESA's Solar Physics Planning Group. A Solar Orbiter-type mission was also proposed to ESA by an international team of scientists in response to the recent call for mission proposals for two Flexi-missions (F2 and F3).

A key feature of the mission is a spacecraft orbit that not only provides multiple, near-Sun passes, but which also carries the Orbiter to moderately high solar latitudes. This, together with the cost constraints associated with Flexi-type missions, represented a significant challenge in terms of mission and system design.

Introduction

The results from missions such as Helios, Ulysses, Yohkoh, SOHO and TRACE (Transition Region and Coronal Explorer) have advanced enormously our understanding of the solar corona and the associated solar wind and three-dimensional heliosphere. We have now reached the point, however, where in-situ measurements closer to the Sun, together with high-resolution imaging and spectroscopy from a near-Sun and out-of-ecliptic perspective, promise to bring about major breakthroughs in solar and heliospheric physics. The acquisition of these measurements is the primary scientific objective of the Solar Orbiter Mission that has been studied in the framework of ESA's Solar Physics Planning Group, and which was proposed as a possible Flexi-mission (F2/F3) candidate.

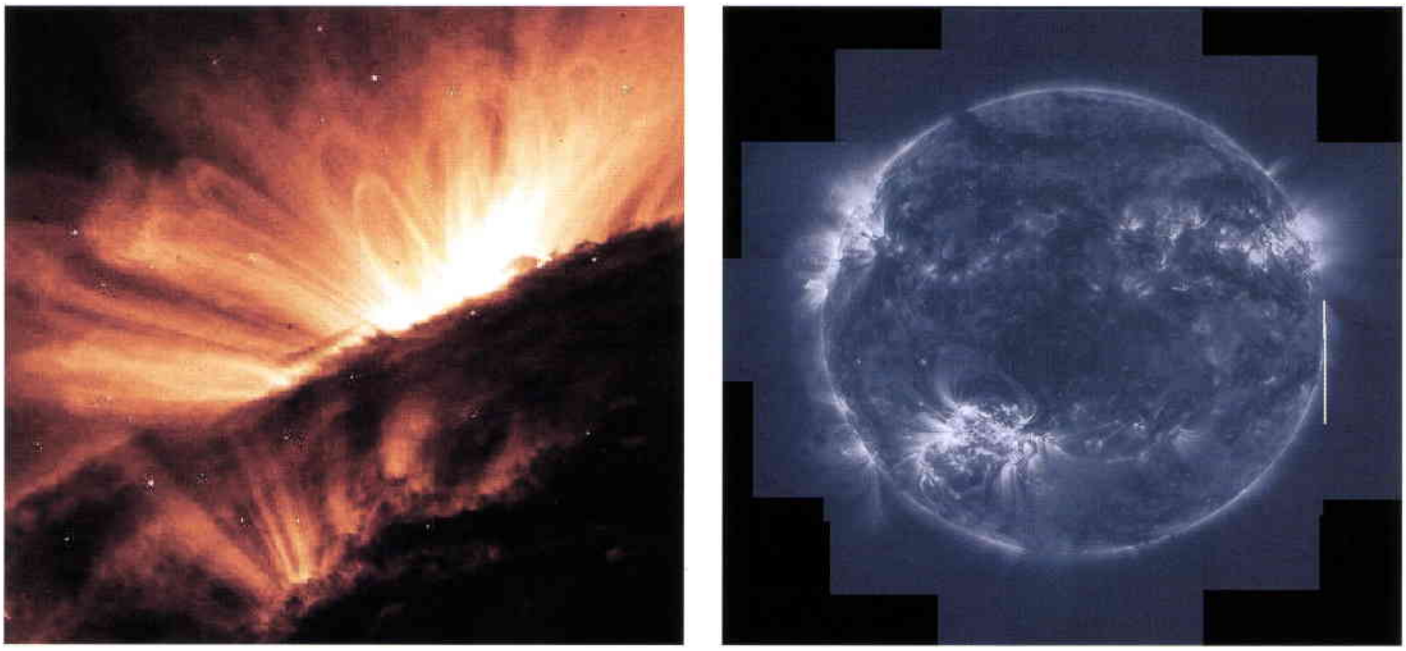
The Solar Orbiter Mission as studied embodies several totally novel aspects that would allow unique science investigations to be performed. For example:

- By approaching the Sun to within 45 solar radii, or 0.21 Astronomical Units (AU), Solar Orbiter would enable close-up remote-sensing observations of the magnetised solar atmosphere, providing: (a) unprecedented high-resolution, and (b) in-situ measurements of the unexplored innermost region of the heliosphere.
- By matching the speed of the Orbiter near perihelion to the Sun's rotation rate, unique helio-synchronous observations could be acquired, enabling a better understanding of the links between solar and heliospheric processes.
- By increasing the inclination of the orbital plane with respect to the solar equator, the first-ever out-of-ecliptic imaging and spectroscopic observations of the solar poles and equatorial corona from latitudes as high as 38° could be acquired.

Scientific goals

Close-up observations of the solar atmosphere: the Sun's magnetised plasma

High-resolution imaging of the solar atmosphere from Solar Orbiter would represent a major step forward, providing an order-of-



magnitude improvement in spatial resolution over past missions. When operated in concert, the scientific instruments envisaged for Solar Orbiter would enable:

- a thorough analysis of the time-variability, evolution and fine-scale structure of the dynamic chromosphere, transition region and corona
- the study of the Sun's magnetic activity on multiple scales
- the investigation of energetic-particle acceleration, confinement and release
- the plasma and radiation processes underlying the heating of the chromosphere and corona to be revealed.

The Sun is the only star that can be imaged at a level of detail such that the physical processes responsible for magnetic activity can be resolved.

Helio-synchronous observations: linking the photosphere and corona to the heliosphere

Studies of the evolution of solar features such as active regions, loops, prominences or sunspots are greatly complicated by the fact that their evolution time scales are comparable to the solar rotation period. As a result, the evolution is entangled with other effects such as centre-to-limb variations, foreshortening and projection effects. In order to disentangle these effects, it is necessary to have an instrument platform that co-rotates with the Sun. The Solar Orbiter would, for the first time, provide such an opportunity and would thus help to resolve old and otherwise intractable problems related to the solar dynamo and the diffusion of the magnetic field across the solar surface. It would also allow, again for the first time, the evolution of sunspots and active regions to be followed, as well as the influence of the observed changes on the corona above.

In-situ measurements in the inner heliosphere: particles and fields

According to recent SOHO findings, coronal expansion arises because of the high temperature of the coronal ions. The temperature of the minor species can reach as much as 10^8 K at a few solar radii. In contrast, coronal electrons are comparatively cool. In fact, they hardly reach the canonical coronal temperature of 10^6 K, and consequently the electric field has a minor role in accelerating the ions. The high pressure of the coronal ions and the low pressure of the local interstellar medium

Figure 1. High-resolution image of the Sun recorded by the NASA Transition Region and Coronal Explorer (TRACE) mission

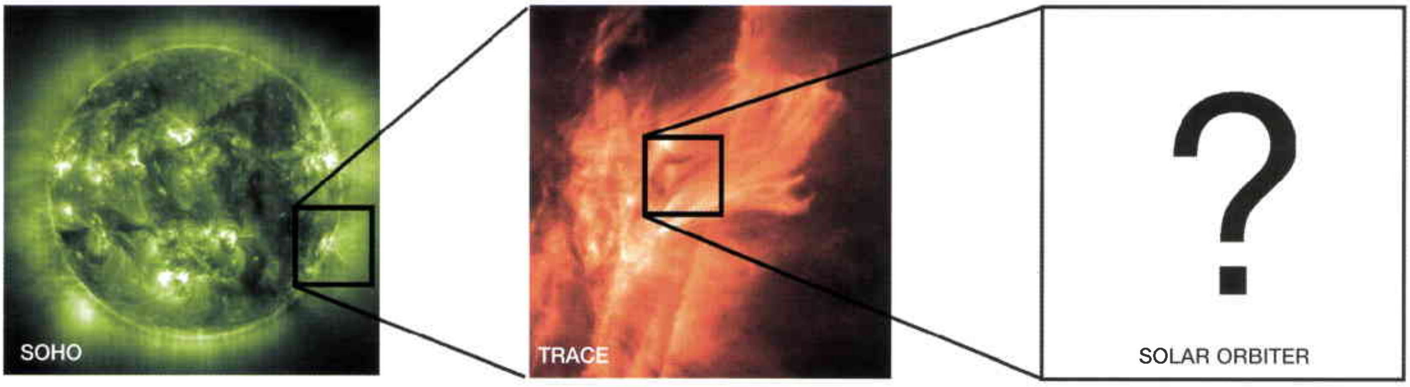


Figure 2. The Sun as seen by the Extreme-ultraviolet Imaging Telescope (EIT) on SOHO (left) and TRACE (centre). Pixel sizes on the Sun of EIT and TRACE are 1850 and 350 km, respectively. The Extreme Ultra-Violet (EUV) imager envisaged for the Solar Orbiter will have a pixel size of 35 km on the Sun

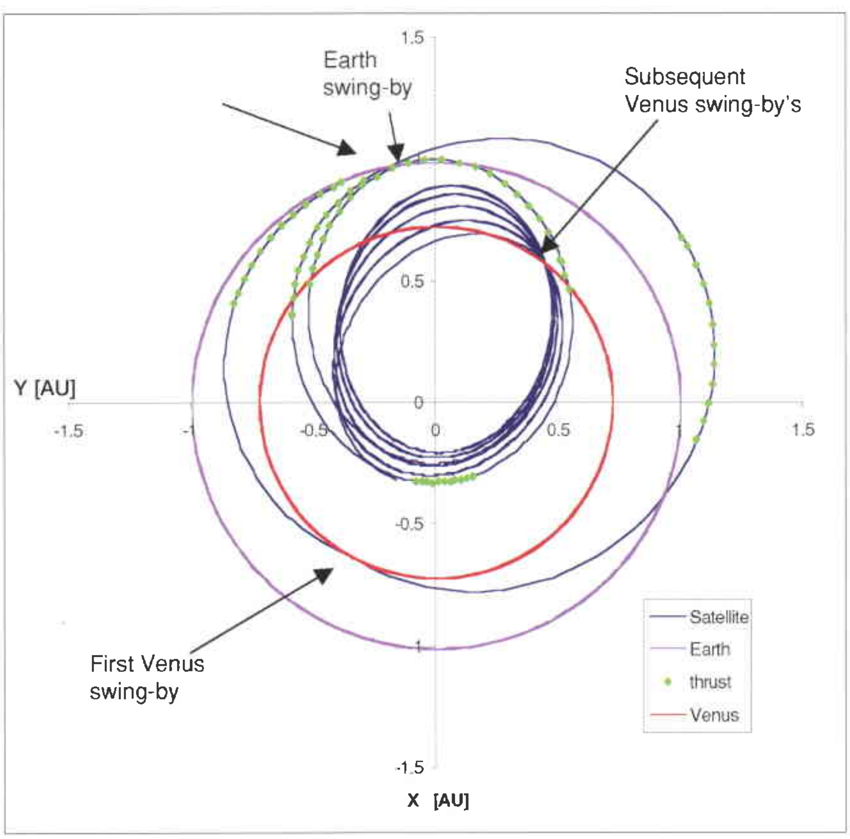
lead to a supersonic solar wind extending to large distances from the Sun (typically 100 AU). Yet, even given the insights resulting from SOHO, the detailed physical mechanisms that heat the corona and accelerate the plasma to supersonic speed remain poorly understood. This is largely because the resolution of the SOHO imagers and spectrometers was still not sufficient. Furthermore, the solar-wind plasma has never been sampled directly closer to the Sun than 0.3 AU (the perihelion distance of Helios).

The Solar Orbiter would provide the first opportunity of going closer to the Sun than the Helios space probes. Furthermore, it would carry powerful, high-resolution optical instruments in addition to the in-situ experiments. In particular, the envisaged plasma and field instruments would have high temporal resolution, ranging between 0.01 s and 1 s, offering unique possibilities to resolve physical processes at their intrinsic scales. This would in turn provide new insights into the plasma kinetic processes that structure the Sun's atmosphere, heat the extended corona, and accelerate both the solar wind and energetic particles.

The excursion out of the ecliptic: the Sun's polar regions and equatorial corona

Despite the great achievements of Ulysses and SOHO, significant scientific questions concerning the nature of the Sun, its corona and the solar wind remain unanswered. A Solar Orbiter mission combining high-latitude vantage points and a suite of remote-sensing instruments is the next logical step. For example, progress in understanding the solar dynamo will depend on how well we understand differential rotation and the circumpolar and meridional flows near the poles of the Sun. The poles appear to rotate comparatively slowly, but the polar vortex is still not well characterised due to the serious limitations of in-ecliptic observations. The Solar Orbiter would provide the first opportunity to measure directly the magnetic field at the poles, as well as the surface and subsurface flows there.

Figure 3. Ecliptic projection of the Solar Orbiter's trajectory



The large-scale unipolar character of the magnetic field in coronal holes gives rise to the fast solar wind that expands super-radially into the heliosphere. The Solar Orbiter offers the opportunity to sample the fast wind at distances where the plasma still retains some memory of the acceleration processes. With regard to the sites of acceleration, SOHO spectroscopic measurements suggest that the supergranulation network plays a special role. High-latitude observations would provide a definite answer.

Even with new, dedicated missions such as STEREO, it is impossible to determine the mass distribution of large-scale structures such as streamers, and the true longitudinal extent of Coronal Mass Ejections (CMEs). The Solar Orbiter would provide the first observations of the complete equatorial corona and its expansion in the equatorial plane. Furthermore, it would provide crucial information on the three-dimensional form of CMEs.

Scientific payload

In order to achieve the wide-ranging aims described above, the Solar Orbiter must carry a suite of sophisticated instruments. Owing to the Orbiter's proximity to the Sun, the instruments could be smaller than comparable instrumentation located at the Earth's orbit. The payload envisaged includes two instrument packages, optimised to meet the specific solar and heliospheric science objectives:

- Heliospheric in-situ instruments: solar-wind analyser, radio- and plasma-wave analyser, magnetometer, energetic-particle detectors, interplanetary dust detector, neutral-particle detector, solar-neutron detector.
- Solar remote-sensing instruments: extreme-ultraviolet (EUV) full-Sun and high-resolution imager, high-resolution EUV spectrometer, high-resolution visible-light telescope, and magnetograph, EUV and visible-light coronagraph, radiometer.

Mission profile

The mission profile needed to fulfil the scientific requirements is in many respects the fundamental design driver in the Solar Orbiter mission. In order to achieve the desired operational orbit within a reasonable transfer time, having a perihelion as close as possible to the Sun and with a high orbital inclination with respect to the solar equator, a strategy based on low-thrust Solar Electric Propulsion (SEP) and planetary gravity-assist manoeuvres was adopted. In the context of the study, the baseline orbit is achieved using a standard Soyuz-Fregat launcher from Baikonur, together with interleaved Earth/Venus gravity assists and SEP firings. Operations are assumed to be conducted from the European Space Operations Centre (ESOC) using the 35-m ground station near Perth, in Australia.

The baseline orbit provides a satisfactory scientific mission, reaching a heliographic latitude of about 40° (end of extended phase), with a minimum Sun–spacecraft distance of 0.21 AU (beginning of nominal mission). Equally importantly, the design of the spacecraft is still thermally feasible (Figs. 4 & 5). The celestial constellation of Sun, Venus and Earth lead to a launch window of 3 weeks every 19 months.

The spacecraft trajectory consists of three phases (Fig. 3, facing page):

- Cruise phase (0 – 1.86 y): this starts with the spacecraft's separation from the launcher, and ends at the start of scientific operations (some science may be performed during the cruise phase); there are thrust phases, Venus swing-bys (for semi-major-axis changes), and an inclination increase.
- Nominal mission phase (1.86 – 4.74 y, duration: 2.88 y): the prime scientific mission is performed; there are two Venus swing-bys for inclination increase during seven orbits (orbit period is 150 days on average).
- Extended mission phase (4.74 - 7.01 y, duration: 2.28 y): contingent on additional funding, the mission is extended; further gravity-assist manoeuvres enable the high-inclination requirement to be more closely met; there are two Venus swing-bys for inclination increase during six orbits (orbit period is 150 days on average).

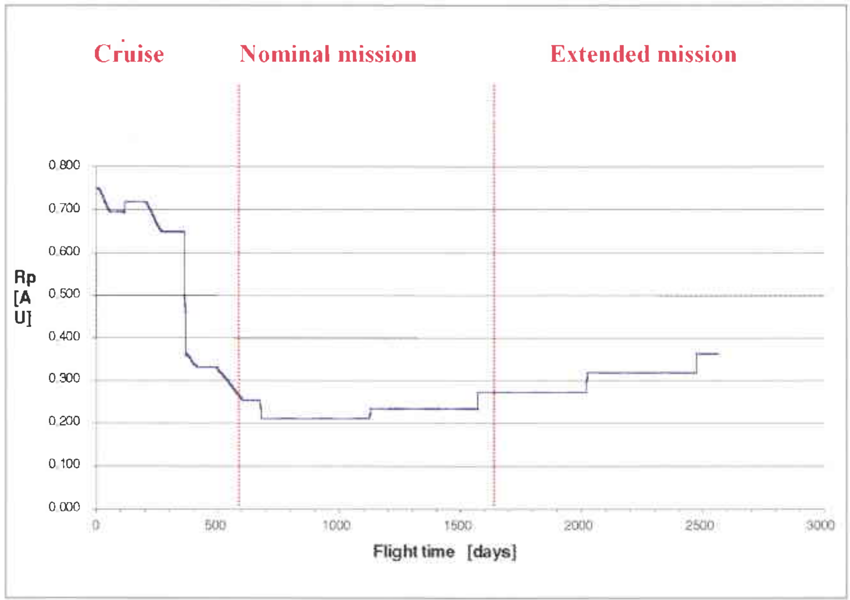


Figure 4. Perihelion distance as a function of time

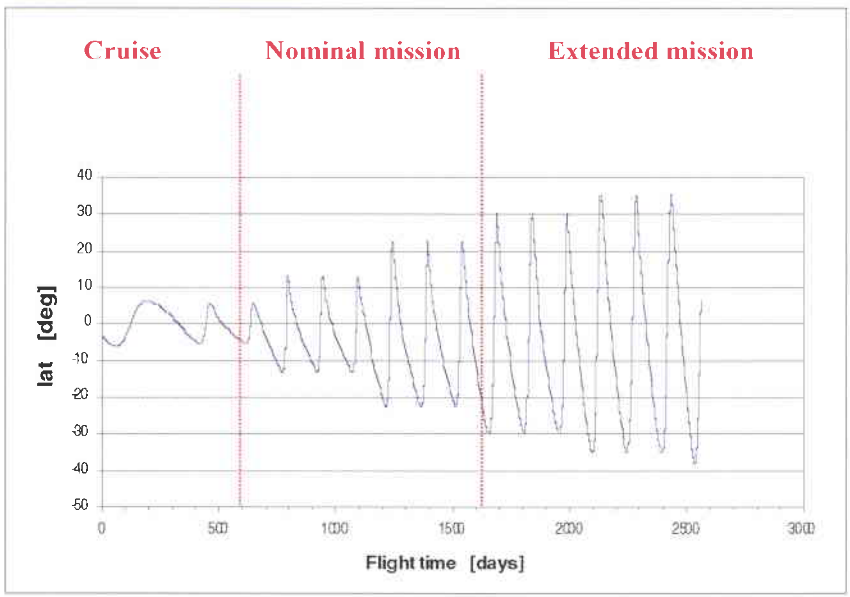


Figure 5. Solar latitude as function of flight time

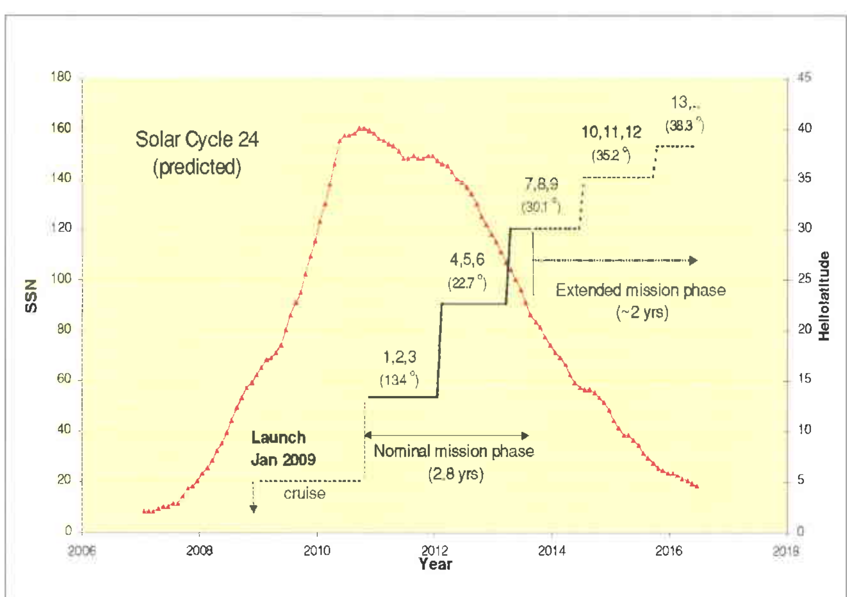


Figure 6. The various mission phases plotted together with the predicted solar activity cycle (represented by Smoothed Sunspot Number, SSN - red triangles). For a launch in January 2009, the near-Sun phase of the Solar Orbiter mission (orbits 1, 2 and 3) would take place under conditions of high solar activity, whereas the higher-latitude orbits would occur during the declining phase of the solar cycle

System design

Design requirements and drivers

As noted above, the system design for the Solar Orbiter was driven by requirements imposed by the mission profile, as well as the cost objectives that were set in the context of the study. The spacecraft is designed to get as close as possible to the Sun as the available materials and engineering will allow (0.21 AU), and the increase in solar radiation while approaching the Sun is, of course, the most challenging aspect of the mission. The solar constant at a distance r in astronomical units (AU) is given by $C_s(r)=C_{so}/r^2$, where C_{so} is the solar constant measured at 1 AU, i.e. 1367 W/m^2. Figure 7 illustrates the maximum heat load that the Solar Obiter will be subjected to during its mission. The locations of two other spacecraft (Cassini and Mercury Orbiter) are shown for comparison. The orbit is as highly inclined to the Sun's equator as the launcher and propulsion capability will allow. The power demand is higher during cruise, the majority being needed for electric propulsion. The solar array must be sized to provide adequate power at the furthest distance from the Sun. The solar array is also a thermal burden on the system: when electric propulsion is no longer needed, the surplus area must be protected by thermal louvers. The spacecraft size and shape is directly linked to the envelope of the largest instruments and the service-module performance.

The major design-driving features for the spacecraft were:

- Instrument requirements (mainly field of view, pointing stability, operations and size).
- Launcher mass envelope and interfaces.
- Earth communication, mainly accommodation of the High Gain Antenna (HGA), and HGA pointing for data transmission.
- Use of existing hardware to minimise both risk and cost.

Main system-design features

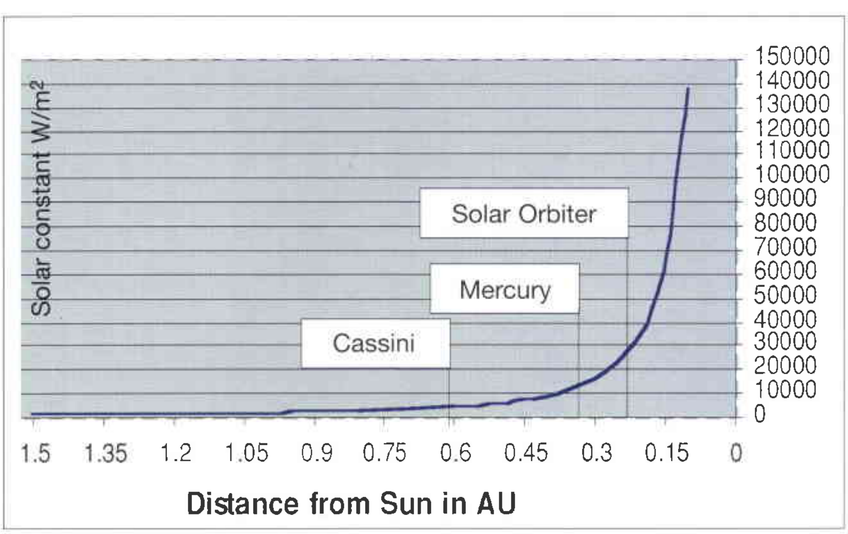
The three-axis-stabilised 1308 kg spacecraft (at launch, incl. adapter; see Fig. 8) is box-like in shape, about 3.0 m long, 1.6 m wide and 1.2 m deep. It has internally mounted instruments, a two-axis steerable High Gain Antenna (HGA), two sets of one-degree-of-freedom steerable solar arrays, and a Solar Electric Propulsion (SEP) system.

The spacecraft comprises two modules, a Service Module (SVM) and a Payload Module (PLM). The benefits of this approach include flexibility during the Assembly, Integration and Verification (AIV) programme – the two modules can be integrated and tested concurrently – as well as allowing easy access to the propulsion system. Carbon-Fibre Reinforced Plastic (CFRP) is used for the structure to achieve the required thermo-elastic stability, while the PLM includes a central cylinder to ensure the required stiffness.

The ±Y sides of the PLM accommodate the cruise solar array (two wings, three panels per wing) and the top shield radiators. The optical instruments are located directly beneath the top shield (Fig. 9), pointing along the +X axis. They are attached to the central cylinder isostatically and are open to cold space on the ± Z sides. The instruments' electronic boxes are mainly mounted on the PLM's bottom panel.

The SVM accommodates the second solar array and the SEP/equipment radiators on the ±Y panels. The thrusters are attached to the +Z panel. The propellant tank is mounted on a dedicated ring inside the central SVM cylinder, at the spacecraft's Centre-of-Gravity (COG). This design allows for possible changes in COG height during spacecraft development. The equipment boxes are mounted internally on the SVM panels.

Figure 7. Solar Constant behaviour as a function of distance from Sun



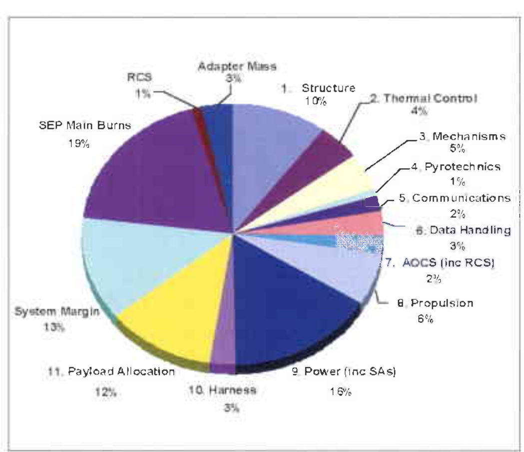


Figure 8. Satellite mass breakdown

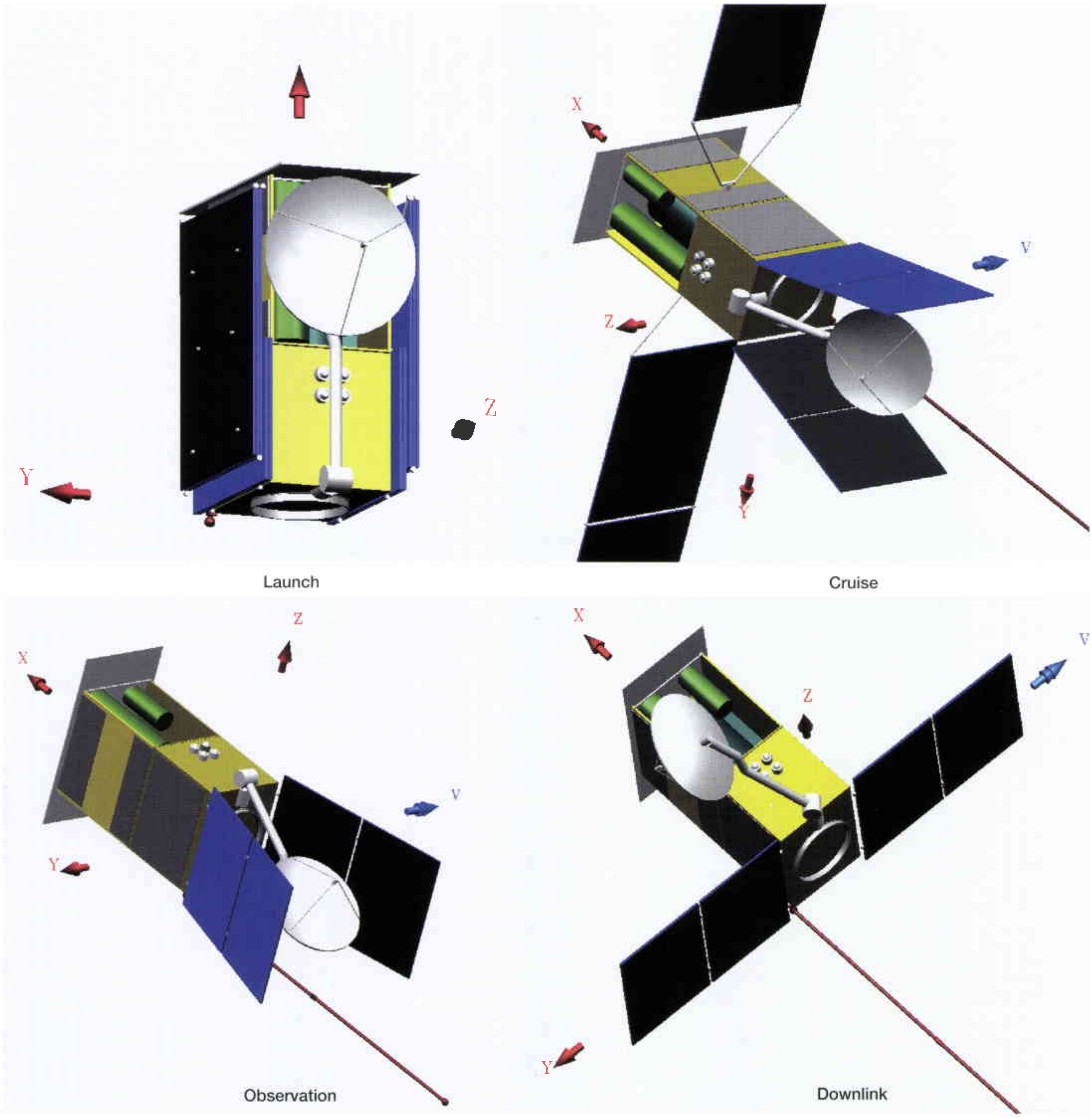


Figure 9. Solar Orbiter configurations

The difficulties encountered during the study associated with the implementation of this mission were many and varied.

Thermal control

The extreme environments to be encountered by the Solar Orbiter throughout the mission require a sophisticated thermal design that can accommodate a wide range of heat loads. At one end of the scale, the spacecraft approaches the Sun to within 0.21 AU, whilst at the other it travels as far away as 1.21 AU. This represents a change in solar-energy input by a factor of more than 30. Another important, albeit intermittent, source of heat is the SEP system when thrusting.

The proximity to the Sun is particularly demanding for appendages that cannot be protected by thermal shielding. Figure 12 shows the temperature profile (a surface perpendicular to the Sun is considered) with distance from the Sun using different technologies for external coating.

Special attention needs to be given to the selection of a suitable coating that has an α/ε ratio below 0.25, even after ageing effects have been taken into account. Furthermore, the selected external coating needs to be electrostatic-discharge (ESD) and spall resistant. This is a considerable technological challenge.

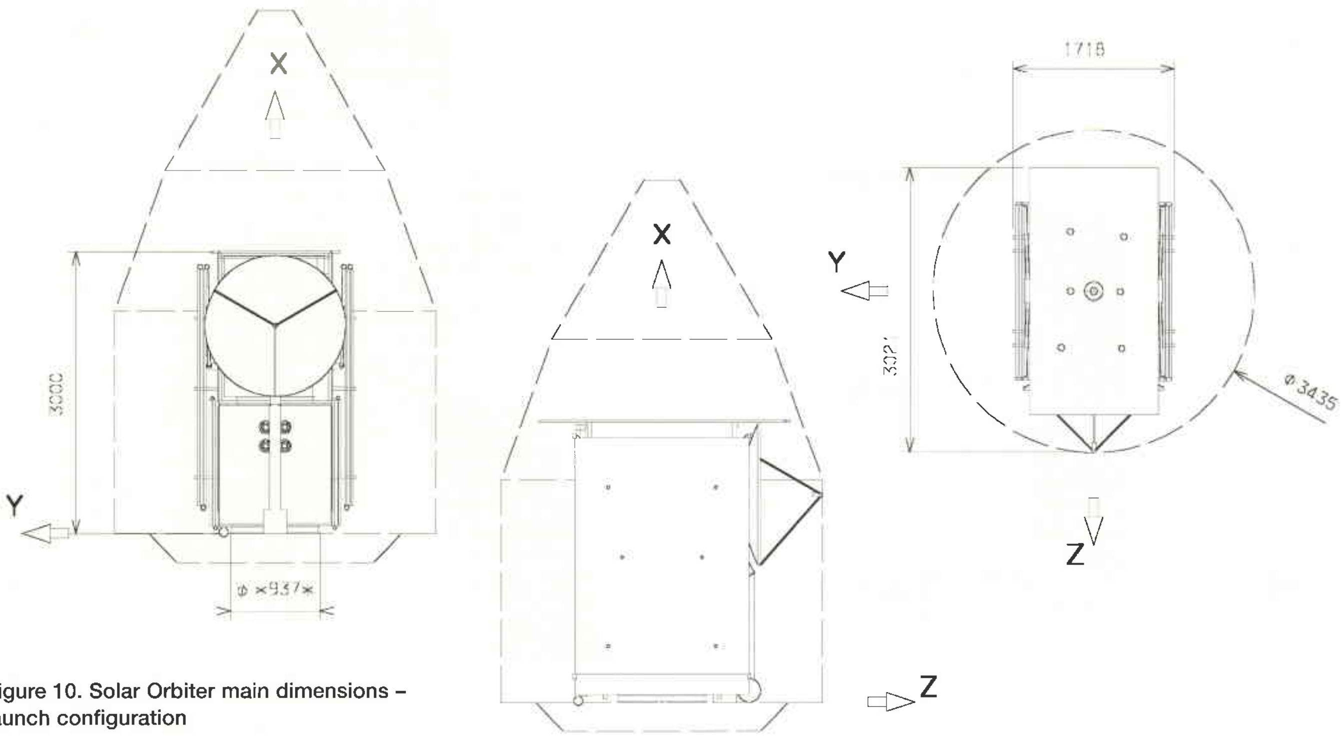


Figure 10. Solar Orbiter main dimensions – launch configuration

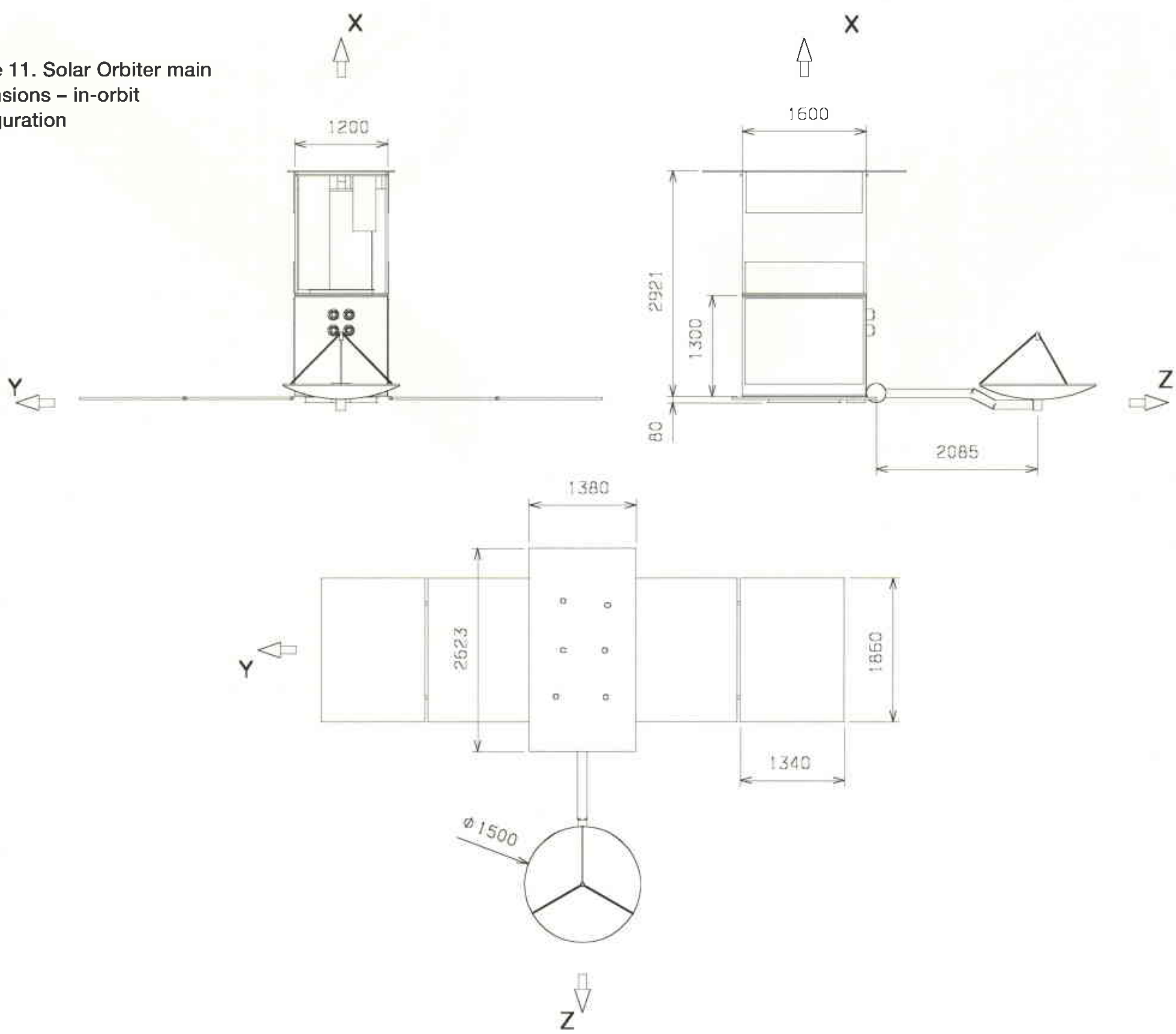


Figure 11. Solar Orbiter main dimensions – in-orbit configuration

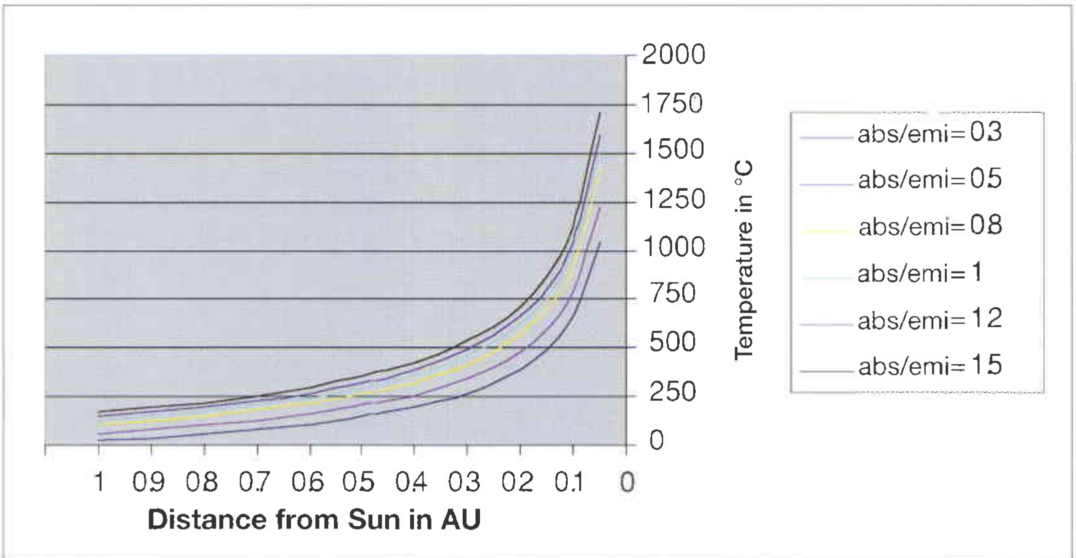


Figure 12. Temperature of a generic satellite surface as a function of absorptivity/ emissivity (abs/emi) ratio and as a function of solar constant (theta = 0°).

To ease the thermal control and to meet instrument requirements, the spacecraft is three-axis-stabilised and always Sun-pointed (X-axis), except during SEP firing. The Sun-pointing face is made as small as possible to minimise solar heat input, and the remaining satellite walls are used as radiators. With that assumption, only one thermal shield made of three titanium foils plus 15 layers of Kapton/Mylar/Dracon net Multi-Layer Insulation (MLI) is needed to protect the spacecraft bus and Z-faces during the most demanding mission phases (design cases). The external surface is painted so as to have a very low α/ε (see above). In addition, behind the structure, another 15 layers of MLI are used to insulate the spacecraft further from any remaining solar flux leaking through the MLI and to avoid heat leaks during the coldest phases.

The thermal shield has been tailored to shadow spacecraft walls during thruster firing (Sun depointing) at minimum Sun–spacecraft distance. Furthermore, it has also been designed to keep the HGA and solar-array mechanisms in shadow such that the temperatures they experience will always remain within standard Earth-orbit limits (i.e. temperatures experienced at 1 AU) to increase reliability.

To cool down the sunshield and avoid heat leaks inside the spacecraft, dedicated radiators are accommodated on the spacecraft's walls (± Y). Heat pipes are used to increase thermal conductance between the sunshield structure and its radiators.

Power supply

Electrical power for the Solar Orbiter is provided by solar arrays. Photovoltaic solar cells convert light directly into electricity, but the efficiency of this process decreases with increasing temperature. Since the Solar Orbiter will experience a wide range of thermal environments during its mission, including exposure to extremely high temperatures at perihelion, the design of the solar arrays constituted quite a challenge.

In order to be compliant with these mission and spacecraft requirements, it was necessary to implement two sets of solar arrays. The first one is used during the cruise phase and is designed mainly to provide sufficient power for the solar electric propulsion module. It is not possible to retain this array during the observation phase because of difficulties in maintaining the required instrument pointing stability, so it will be jettisoned after the last firing. The cruise solar array takes advantage of a standard design used for geostationary-orbit missions (for which the maximum allowed temperature is 130°C). It comprises two symmetric wings of three panels each, and is able to provide 6.2 kW at 1 AU. The second solar array will only be used during the observation phase. Its design is different from that of the cruise array, since there is a need to increase the upper temperature limit (max. allowed temperature 150°C). In order to meet this requirement, it is envisaged to use panels made of a honeycomb core with aluminium face sheets on which Optical Surface Reflectors (OSRs) are installed. The use of aluminium for the face sheets is necessary to reduce the thermal gradient within the panels when exposed to the Sun.

The definition of the solar-array pointing strategy during both the cruise and observation phases of the mission such that the maximum allowed temperatures are never exceeded was a challenge. Figure 13 shows the effect of the Sun's incidence angle on the temperature of the solar arrays.

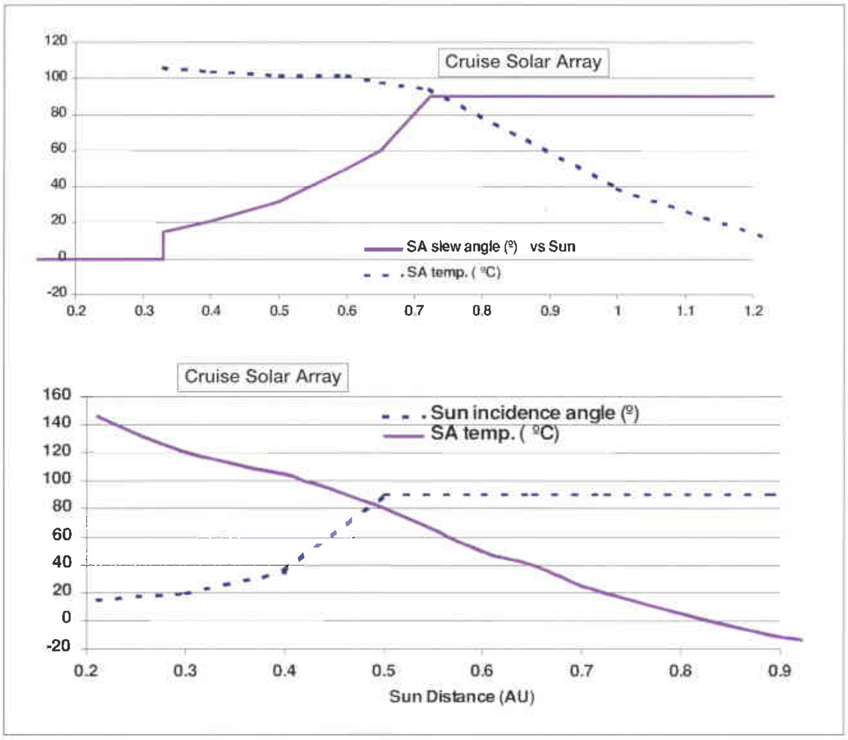


Figure 13. Cruise/Orbiter solar-array temperature as a function of distance from the Sun and solar incidence angle

Data collection/dumping
During the cruise phase, the downlink data consist mainly of housekeeping information (up to 1 kbps). Communication via wide-beam Low-Gain Antennas (LGAs) at X-band is the baseline for both up- and down-linking. During the observation phases, the spacecraft–Earth distance will change from orbit to orbit (from 0.3 up to 1.8 AU), and consequently the downlink data rate that can be supported will vary. The orbital period is 150 days on average, and the scientific data acquired during each orbit must be transmitted to the ground before commencing the next set of observations. Because of these limitations, three sets of high-data-rate scientific observation periods of ten days each are considered as a baseline, with the observation strategy then tailored for each orbit. These periods are (Fig.14):
– 5 days before to 5 days after maximum southern solar latitude
– 5 days before to 5 days after maximum northern solar latitude
– 5 days before to 5 days after perihelion.

During such periods of high-data-rate acquisition (mainly the remote-sensing instruments operating at 74.5 kbps; see Fig. 14), on-board data storage in a 240 Gbyte memory is foreseen. Low-rate data acquisition at 11.5 kbps (mainly the particles and fields instruments) is possible throughout the majority of the orbit.

The severe thermal environment when approaching the Sun does not allow the use of the HGA to downlink data to Earth. Therefore, in order to avoid antenna pattern distorsion as well as technological problems, a minimum Sun–spacecraft distance of 0.5 AU for HGA operation was adopted. This limits the downlink via the HGA to approximately 110 days per orbit. Whenever possible, the low-rate data will be downlinked in real time, otherwise it will also be stored onboard and dumped later.

Conclusion
Clearly, the Solar Orbiter is a very exciting and ambitious mission for the solar-physics community. As has been shown in this article, it also represents a formidable challenge from the point of view of system design, the more so because the project must be executed within the stringent cost cap of an F-class mission. An important element in achieving this goal is the use of hardware and new technologies that are

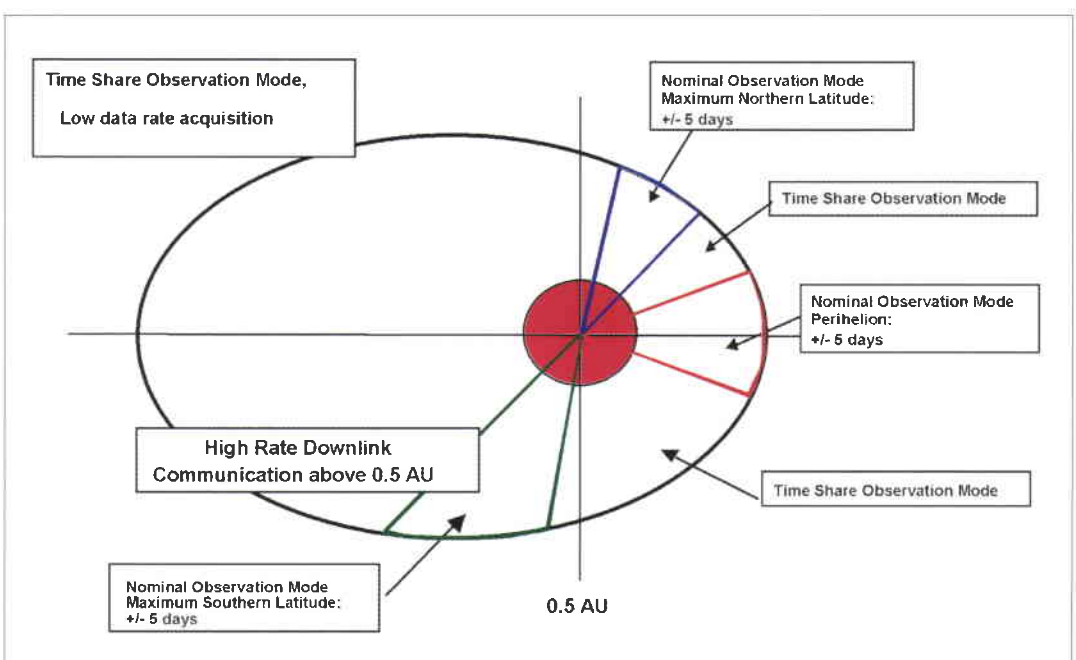


Figure 14. Modes of operation during nominal and extended mission phases

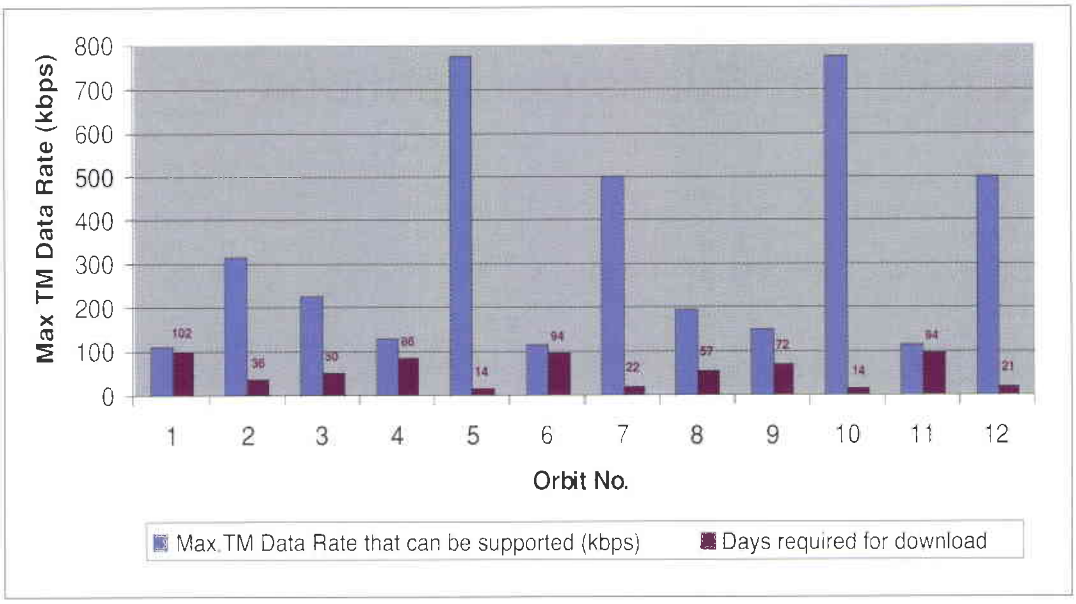


Figure 15. Downlink capabilities for the different orbits. The distance between the spacecraft and the Earth varies considerably from one orbit to the next, and the time taken to downlink the data acquired during each high-data-rate observation period varies proportionately

already being developed (or will be developed) in the framework of the ESA Cornerstone project Bepi-Colombo. This strategy is necessary in order to arrive at an acceptable mission cost coupled with low risk.

The study has shown that, in general, the mission is technically feasible, given the assumed programmatic and technical requirements. A few areas still need to be refined/optimised, including the detailed accommodation of the scientific payload.

Acknowledgements

The authors have used documents and materials prepared by the Solar Orbiter Concurrent Design Facility Team. The feasibility assessment of such a challenging mission has been possible thanks to the excellent work performed by the team, led by M. Bandecchi, to whom the authors are sincerely grateful. The authors also gratefully acknowledge the inputs from the Solar Orbiter Assessment Study Team, and Y. Langevin's support in designing the mission trajectory

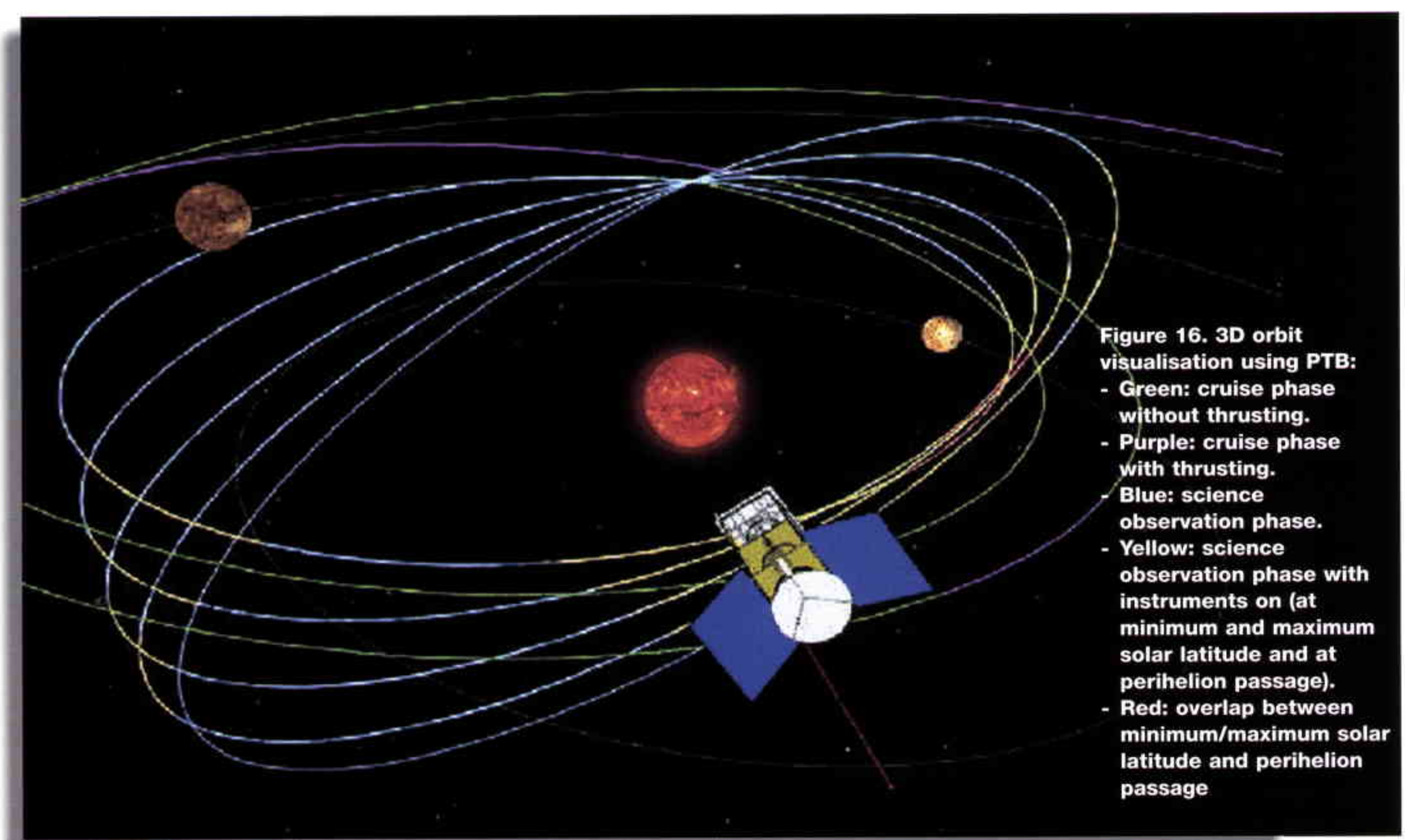


Figure 16. 3D orbit visualisation using PTB:
- **Green: cruise phase without thrusting.**
- **Purple: cruise phase with thrusting.**
- **Blue: science observation phase.**
- **Yellow: science observation phase with instruments on (at minimum and maximum solar latitude and at perihelion passage).**
- **Red: overlap between minimum/maximum solar latitude and perihelion passage**

TOPSTAR 3000 – An Enhanced GPS Receiver for Space Applications

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This article discusses the main attractions of using GPS receivers for space applications, as well as the specific features of spaceborne and terrestrial and airborne receivers. The performances achievable for several types of space mission are also highlighted with the results of engineering-model simulations performed with the Alcatel TOPSTAR 3000 GPS receiver.

Introduction

GPS receivers are now widely used for Low Earth Orbit (LEO) spacecraft applications for both scientific and commercial programmes. New applications are also under study, such as navigation in Geostationary Earth Orbit (GEO) and Geostationary Transfer Orbit (GTO), space rendezvous manoeuvres and atmospheric re-entry, for which GPS receivers are promising candidates as navigation sensors. Between 1997 and 1999, under a joint ESA/CNES contract, Alcatel developed TOPSTAR 3000, a new generation of GPS receiver dedicated specifically to spacecraft applications (Fig.1). This receiver uses the L1-C/A GPS service and can serve both modular and multi-mission applications.

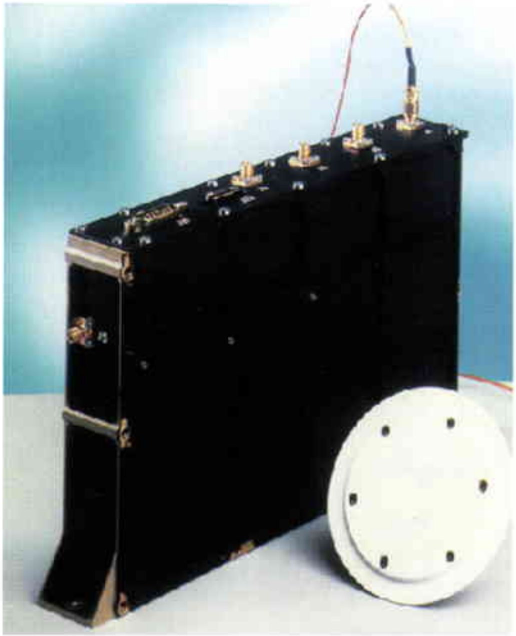

Figure 1. Alcatel TOPSTAR 3000 GPS receiver

The TOPSTAR 3000 receiver has been designed as an autonomous unit, allowing easy adaptation to particular mission requirements and spacecraft interfaces. Intended to cover the radio-navigation needs of both telecommunications and Earth-observation satellites, it features a fully parallel architecture providing 24 signal-processing channels over 1 to 4 antennas with very high sensitivity performances. An embedded orbital navigator provides reliable and highly accurate navigation, and is able to cope with poor visibility as well as complex spacecraft manoeuvres.

Space radio-navigation

Space GPS receiver services

The use of GPS receivers for space missions is becoming quite a common technique, the main applications being:

- *Real-time orbit-determination services:* The receiver provides three-dimensional position and velocity information for both on-board and ground-station use, thereby improving spacecraft autonomy and simplifying the ground tracking and ranging segment. As an example, real-time positioning can be used on-board for computing the Local Orbital Frame co-ordinates, thus improving attitude pointing accuracy versus up-linked filtered position. On-board position determinations can also be down-loaded to ground stations for the monitoring of the spacecraft orbit. This feature is particularly interesting in the case of constellations, where avoiding saturation of the localisation system would require costly duplication of the ground tracking stations.

- *Reference-time services:* The receiver provides accurate reference time synchronised with UTC to better than 1 μs. This level of accuracy can be useful for both telecommunications and Earth-observation missions, as well as for multi-spacecraft time synchronisation.
- *Raw-measurement services:* The receiver provides raw GPS measurements that can be either transmitted to another spacecraft (for relative navigation) or downloaded for ground processing. One example of such ground processing of raw GPS measurements is Kalman-filtering for very precise orbit determination. The accuracy achieved for the radial component is better than 10 cm for a single-frequency receiver and 3 cm for a dual-frequency receiver, and may therefore be useful for scientific Earth-observation missions. Raw measurements from dual-frequency L1/L2 GPS receivers can also be used for atmospheric analyses.
- *Attitude determination services:* This requires the use of three or four GPS antennas connected to the receiver. The latter performs GPS signal-carrier measurements, which can be used to compute the attitude of the spacecraft in real time. Accuracy is mainly limited (0.5° rms) by the effect of multi-paths on the spacecraft structure. Performance can be improved (0.1°) by combining GPS with other attitude sensors.

Space GPS receiver features

In terrestrial or airborne GPS receivers, position and velocity are usually computed by a 'snapshot least-square' method. Position and velocity are considered independent and resolved separately: position is computed from code range measurements and velocity from carrier Doppler measurements. This provides a high degree of robustness, but accuracy is limited by GPS Selective Availability to 100 m and 1 m/s (3D rms)*.

In orbital flight, a spacecraft's motion is governed by Kepler's laws, which define a predictable trajectory for which position and velocity are closely linked. This predictability of movement allows time filtering of the trajectory, leading to an improvement in orbit prediction accuracy. A Kalman filter, called the 'GPS Orbital Navigator' is used, which combines GPS measurements and an orbital force model to improve the availability and integrity of spacecraft localisation as well as the accuracy.

Spaceborne GPS receivers also have to cope with strong signal dynamics during their orbital flight, which requires adapted signal-processing algorithms and dedicated strategies for satellite search and selection.

Space mission applications

Navigation in LEO is the most widely-used application of GPS in space, as these missions involve similar visibility and link-budget constraints to terrestrial applications. For Earth-pointing missions, typical navigation requirements can be met using only one antenna. In the case of large spacecraft roll/pitch manoeuvres, or the likelihood of masking of the single GPS antenna, use of a second antenna can be useful. For Sun- or inertial-pointing missions, the receiver encounters visibility holes during the Earth-shadowing phases, which degrades the accuracy during these periods. Again, the use of a second antenna or the inclusion of an accurate clock within the receiver can limit this drawback.

GPS-based navigation in GEO is still in the experimental phase, due to the present low GPS-signal availability and weak signal-to-noise ratio. These limitations are due to the fact that the GEO satellites are above the GPS constellation and the receiver has to process signals coming from the other side of the Earth (Fig. 2). Very good signal sensitivity in the receiver and the ability to compute position with less than four GPS measurements are therefore required. The lack of visibility also requires the use of a very stable clock inside the receiver to maintain time accuracy during the visibility holes.

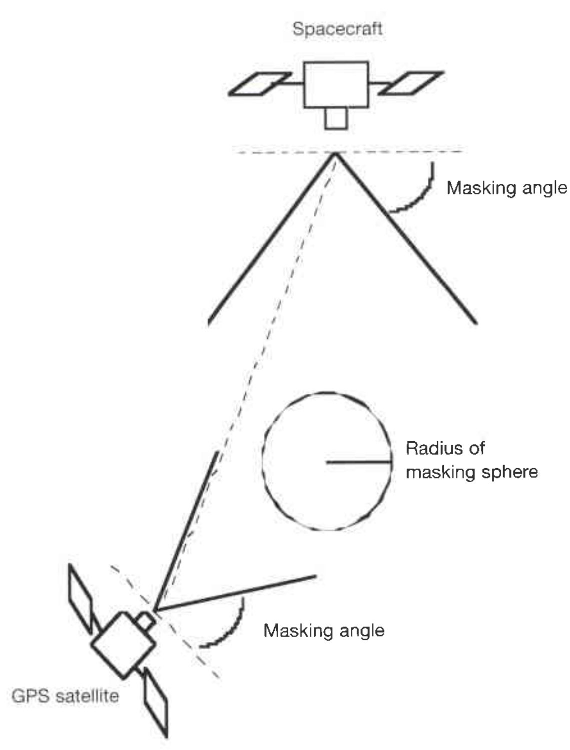

Figure 2. Use of GPS for GEO navigation

* Recent de-activation by the US Dept. of Defense (DoD) of GPS Selective Availability (except during times of crisis) allows an improvement in accuracy by a factor of 4 (approx.)

For attitude applications, the GPS receiver is connected to three or four antennas to provide GPS carrier interferometric measurements. A wide variety of antenna configurations are possible, as well as in-flight upgrading of the antenna configuration.

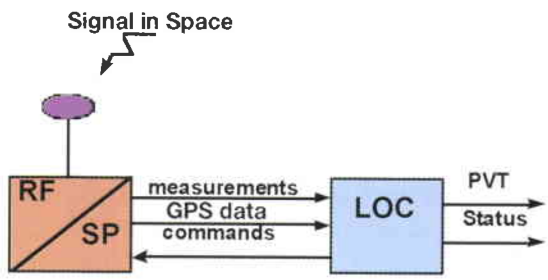

Figure 3. Receiver functional architecture

Relative navigation enables real-time precise positioning of two spacecraft (to better than a few tens of centimetres) and will be used for rendezvous manoeuvres between the Automated Transfer Vehicle (ATV) and the International Space Station (ISS). During the recent flight of ESA's Atmospheric Re-entry Demonstrator (ARD), use of the Alcatel GPS receiver coupled to the inertial sensor significantly improved the navigational accuracy throughout the flight, including the orbital and atmospheric phases.

The TOPSTAR 3000 GPS receiver

A joint ESA-CNES-Industry collaboration

TOPSTAR 3000 has been developed by Alcatel Space Industries, with funding from an ESA, CNES and Matra-Marconi Space partnership. Development was completed in mid-1999 and the first flight model has been delivered for the Stentor geosynchronous mission. Several further flight models are being delivered in 2000–2001 for commercial LEO missions.

The main features of the receiver are:
- 30 C/A code channels, 1 to 4 antennas, fully parallel architecture
- very high sensitivity
- embedded orbital navigator, providing highly accurate and reliable navigation, and able to cope with poor visibility conditions and spacecraft manoeuvres
- modular design, able to accommodate a variety of interface and mission requirements in terms of number of antennas, number of processing channels, class of receiver clock (TCXO or OCXO), data interfaces (RS422 or MIL-STD-1553B), power interfaces (20–50 V primary power bus or secondary voltages)
- fully space-qualified.

The receiver can be operated in two ways: a so-called 'fire and forget' mode, in which the receiver starts as soon as it is switched on and works autonomously (this mode is required for most typical commercial missions), and a 'ground control' mode in which the receiver parameters are closely controlled from the ground via the telemetry/telecommand link (this mode is mainly interesting for advanced experimentation purposes).

Functional architecture

The receiver consists of a signal-processing and a localisation module (Fig. 3).

Signal-processing module

The signal-processing consists of a set of channels that perform GPS signal acquisition and tracking and produce measurements and 50 bps demodulated GPS message data. The measurements include pseudo-range, integrated Doppler, carrier phase and C/N_0.

The main feature of the signal-processing module is the receiver's high sensitivity and hence its ability to acquire and track signals with low C/N_0 (Table1). The signal-acquisition process is a time/frequency search, which involves estimating the energy of the input signal inside a Doppler slot for each C/A code position. The sensitivity of the search is governed by the time spent in integrating the signal in order to extract it from the noise. The integration time is also linked to the *a priori* knowledge of the signal dynamics, and thus also depends on the localisation accuracy.

Table 1. TOPSTAR 3000 sensitivity

Cold-start acquisition	40 dB.Hz
Warm-start acquisition	35 dB.Hz
After-first-fix acquisition	19 dB.Hz
Tracking in code and carrier	29 dB.Hz
Tracking in code only	19 dB.Hz

In order to cope with the wide signal dynamic range of space missions, TOPSTAR 3000 includes several acquisition algorithms:
- 'General acquisition' is used during cold starts when no supporting data are available. The integration time is short, so that the searched for signal does not move out of the Doppler slot during the search. It allows the acquisition of signals with C/N_0 > 40 dB.Hz.
- 'Normal acquisition' is used during warm starts when external supporting data are available (approximate position, velocity, time, almanac). It allows the acquisition of signals with C/N_0 > 32 dB Hz.
- 'Direct acquisition', which requires that the pseudo-range is known *a priori* to ± 10 µs (this occurs when the receiver tracks GPS satellites and computes the spacecraft's position). It allows long integration times and therefore provides very good sensitivity, with acquisition of signals down to C/N_0 > 19 dB Hz.

After the signal has been acquired, the code tracking is performed with a delay-locked loop, and that of the carrier with a third-order modified Costas loop.

Localisation module
The localisation module is dedicated to position, velocity and time computation, GPS SV visibility computation, and signal-processing management. Spaceborne GPS receivers usually rely on two concurrent localisation algorithms: snapshot-least-square resolution and the orbital navigator.

The snapshot resolution uses least-square resolution for computing position, velocity, clock bias and clock drift from pseudo-range and pseudo-range-rate measurements. It requires at least four satellites to be in view and its accuracy is determined by the geometry (GDOP) and by the GPS satellite range error. When Selective Availability is ON, the accuracy is 100 m and 1m/s (3D 1σ) for GDOP = 2.

The benefits of the snapshot resolution for space applications are that it provides:
- a first-fix position after a cold start as soon as four satellites are tracked; this first fix can then be used for the initialisation of the orbital navigator
- localisation during non-orbital phases (re-entry, rendezvous).

The CNES-developed orbital navigator implemented in TOPSTAR 3000 is called DIOGENE (Détermination immédiate d'orbite par GPS et navigateur embarqué). Based on a Kalman filter, it propagates the state vector with an accurate force model and updates it with all available GPS measurements. The state vector consists of the six orbital parameters, the clock drift and the clock bias. The propagation model includes a 40 x 40 Earth gravitational field model, Moon and Sun gravitational effect, and solar pressure effect. DIOGENE can also take into account the description of manoeuvres provided to the receiver (date and duration, amplitude and orientation of the thrust, estimated error, specific impulse, initial mass), and also includes an integrity monitoring function (RAIM). DIOGENE's performance is 10 m in position and 1 cm/s in velocity (3D 1-sigma) for LEO missions. With GPS Selective Availability ON, the time needed for convergence is less than two orbital periods (Table 2).

The orbital navigator provides:
- high accuracy, even with a strong Selective Availability
- embedded integrity function, providing protection against potential GPS constellation anomalies.

Both localisation algorithm outputs are continuously monitored and the receiver provides the best solution (the one with the lowest estimated error). Typically, the snapshot-resolution output will be selected as long as the orbital navigator has not converged or during manoeuvres with large thrusting errors.

The visibility computation is designed to determine which GPS satellites are in the spacecraft GPS antenna's line of sight. For this, the spacecraft attitude is either provided by the on-board computer or defined as a by-default pointing law in the receiver.

The signal-processing management commands and controls the signal-processing module (PRN allocation to GPS channels) and provides supporting data for signal acquisition.

Hardware architecture
The spaceborne GPS receiver consists of a GPS core for signal processing and navigation computation, and optional modules that adapt the receiver to the particular spacecraft interfaces and mission requirements (power supply, data interface, etc.) (Fig. 4).

GPS core
The GPS core is composed of one radio-frequency (RF) and one digital-processing (DP) unit.

The RF unit consists of one to four RF/IF down converters, each of which receives the RF signal from one antenna and performs low-noise pre-amplification and filtering, frequency down-conversion and analogue-to-digital conversion. The key component of each RF/IF down-converter is a bipolar RF ASIC, which features double down-conversion, a low-noise local oscillator, and high-rate multi-bit A/D conversion. The RF unit also includes a medium-class 10 MHz reference clock (TCXO).

The DP unit controls the digital processing of the GPS signal and all the navigation-related computations. It is based on the SPARC Embedded RISC Processor ERC32, and the

Table 2. TOPSTAR 3000 accuracy

In LEO	Position	10 m (3D – 1σ)
	Velocity	1 cm/s (3D – 1σ)
	Time transfer with OCXO	200 ns (3 σ)
	Time transfer with TCXO	1 µs (3 σ)
	Orbital navigator full accuracy	2 orbital periods
In GEO	Position	100 m (3D – 1 σ)
	Velocity	2 cm/s (3D – 1 σ)
	Time transfer with OCXO	1 µs (3 σ)
	Orbital navigator full accuracy	1 orbital period

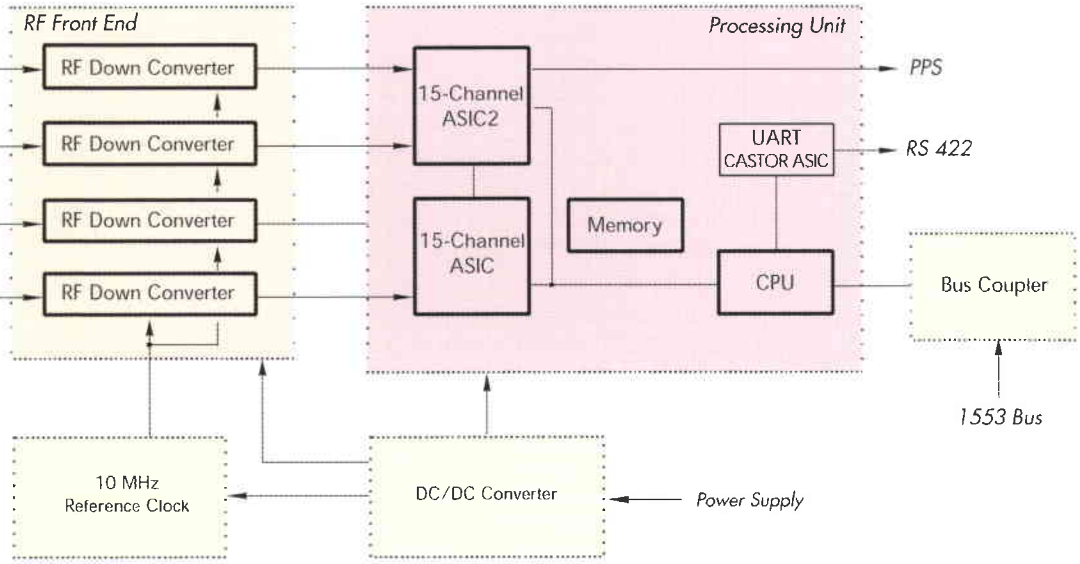

Figure 4. TOPSTAR 3000 receiver design

key component for GPS signal processing is the signal-processing ASIC called PEGASE. This ASIC was developed under an ESA contract in 1995 and features 15 multi-standard channels (GPS, GLONASS and GIC) and interfaces with two RF/IF down-converters.

The GPS core is housed in a compact module powered by secondary supply voltages. Communication is via full-duplex asynchronous RS422 links.

Optional modules
The MIL-STD-1553B interface is a hardware module that can be plugged onto the GPS core. It provides a remote-terminal interface with a redundant MIL-STD-1553 communication bus.

The DC-DC converter is a hardware module that can be stacked on the GPS core. It provides the necessary secondary voltages to the GPS core and other optional modules from a primary 22 to 50 V DC power bus.

A temperature-controlled oscillator (OCXO) can be used to provide a high-stability 10 MHz reference clock for the receiver for missions involving poor GPS visibility or requiring high time-transfer performances.

Space-qualified design
The TOPSTAR 3000 GPS receiver has been designed to fulfil the reliability requirements and cope with space launch and mission demands, including vibration, thermal vacuum, radiation and long lifetimes. It provides resistance to single-event upsets thanks to intensive use of an error-detection-and-correction system, and features latch-up immunity.

Mission analysis

Navigation in LEO
Performance in LEO mainly depends on measurement availability and the accuracy of the orbital filter. Assuming that 6 to 12 GPS satellites are permanently visible in LEO, the availability of the measurements depends primarily on appropriate GPS antenna implementation and orientation, and on receiver sensitivity.

Figure 5 shows the 3D-position true error of the orbital filter resolution for a typical LEO mission (altitude 800 km, inclination 98° and antenna zenith-pointed). The 3D-position accuracy reaches 10 m (rms). The estimated figure of merit (FOM) accuracy computed by the orbital filter is also plotted.

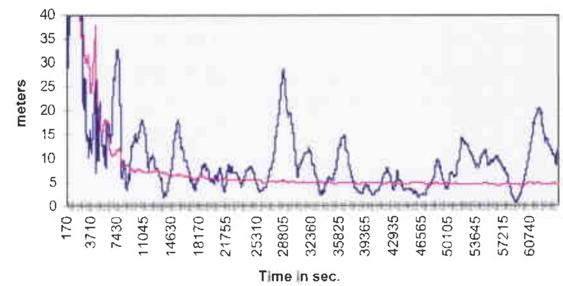

Figure 5. Positioning accuracy (LEO Earth-pointed)

For LEO inertially pointed missions, the number of visible GPS SVs varies between 0 and 8 at the same rate as the spacecraft orbital period, because the GPS constellation is no longer visible to the inertially pointed antenna when the spacecraft is in the Earth's shadow.

Figures 6 and 7 show the number of tracked signals and the true 3D-position error in the orbital filter resolution for a LEO mission with a Sun-pointed GPS antenna (altitude 800 km, inclination 98°). The best 3D-position accuracy is again 10 m (rms).

Navigation in GEO
Performance in GEO depends primarily on the ability of the receiver to cope with very weak

GPS signals and with poor visibility conditions. Navigation in GEO using the GPS antenna main lobe results in 0 to 3 visible satellites, and the minimum signal power is limited to 30 dB.Hz. Navigation in GEO using the GPS antenna main and side lobes results in 2 to 6 visible satellites, but the minimum signal power falls to 20 dB Hz.

Navigation in GEO using side lobes of GPS SV transmitting antenna

Navigation in GEO is dependent on the GPS antenna transmission pattern, which typically involves a 22° main-lobe aperture and a 38° second-side-lobe aperture (Fig. 8).

Figure 9 shows the number of tracked GPS signals when using both the main and side lobes of a GPS SV transmitting antenna (the number of available measurements is doubled compared with using the main lobe only). The signal received from the GPS antenna side lobes is very weak.

Figure 10 shows a GPS signal tracked successively on the main and the side lobes. The signal is first tracked in the main lobe after acquisition at a C/N_0 of 45 dB.Hz. The signal power then decreases as the GPS antenna main lobe decreases and is lost when the C/N_0 falls below 19 dB Hz. The signal is reacquired 30 min later when the C/N_0 reaches 22 dB.Hz and is tracked for 1 h on the side lobe with a level varying between 22 and 27 dB.Hz. Thus, the GPS signal was tracked for 1 h on the main lobe and 1 h on the side lobe, thereby increasing measurement availability and navigation accuracy. With such a weak signal, the receiver uses the code-only acquisition and tracking technique and the velocity provided by the orbital navigator (patented technique).

Use of on-ground pseudolite beacons for GEO navigation

Navigation in GEO with GPS-like on-ground pseudolite beacons is also under study because it brings the advantages of constant geometry, higher signal power, and a signal free from any Selective Availability constraints.

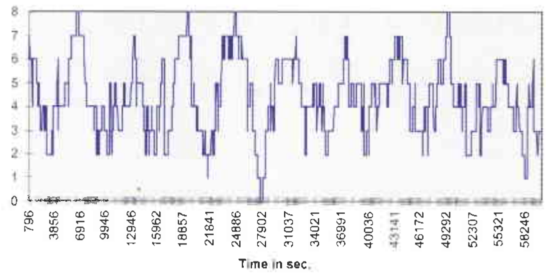

Figure 6. Tracked signals (LEO Sun-pointed)

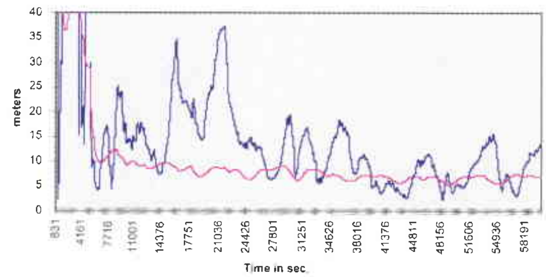

Figure 7. Positioning accuracy (LEO Sun-pointed)

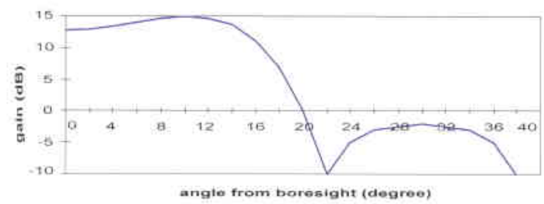

Figure 8. GPS satellite antenna gain pattern

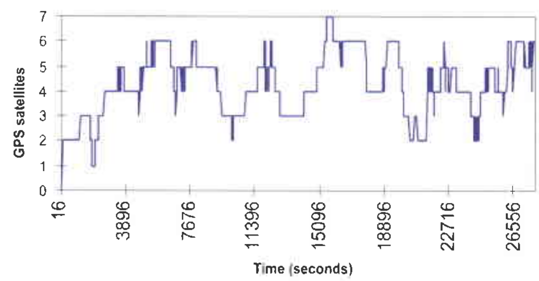

Figure 9. Tracked GPS signals in GEO

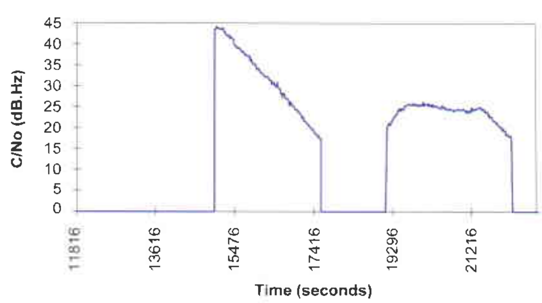

Figure 10. Signal tracked in GEO

Conclusion

GPS receivers are already being widely used for navigation in LEO. For GEO/GTO applications, the use of high-sensitivity and high-accuracy receivers such as TOPSTAR 3000 seems very promising for future commercial applications, and will be demonstrated during the Stentor mission. The use of GPS-like signals transmitted from on-ground beacons and processed by the TOPSTAR 3000 will also be experimented with during the Stentor flight (so-called 'ranging-per-pseudolite' experience).

The de-activation of GPS Selective Availability allows the real-time positioning accuracy in LEO to be improved to 1 m (rms), whilst the availability of two GPS civil frequencies in the near future will further facilitate atmospheric scientific studies. The advent of the Galileo constellation will also contribute substantially to the development of space radio-navigation services.

Searching for Small Debris in the Geostationary Ring

– Discoveries with the Zeiss 1-metre Telescope

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More than 800 satellites and rocket upper stages have been inserted into the geostationary ring or its vicinity over the years, but only about 250 to 270 of these satellites are currently being used operationally. Geostationary satellites are therefore increasingly at risk of colliding with uncontrolled objects. Contrary to the situation with satellites at very low altitude, there are no effective natural removal mechanisms for objects in Geostationary Earth Orbit (GEO). Ground-based radars and optical telescopes belonging to the United States' Space Surveillance Network (SSN) are able routinely to detect objects larger than 1 m across in GEO. ESA has recently upgraded a telescope at the Teide Observatory in Tenerife (E) with an optimised debris-detection system. Its early observations show a hitherto unknown but significant population of uncatalogued objects with diameters as small as 10 cm in the geostationary ring. Objects smaller than 10 cm are also expected to exist, but these are unobservable even with the 1 m Teide telescope. Further observations are urgently needed to determine the extent and origin of this debris population, and the resulting hazard to operational spacecraft.

Introduction

One of the most important and valuable regions in space for telecommunications, Earth observation and space science is the Geostationary Earth Orbit (GEO). The concept of the geostationary orbit was born many years before rockets carried satellites into space. In his book 'Das Problem der Befahrung des Weltraums – Der Raketenmotor' issued in 1929 under the pseudonym Hermann Noordung, Hermann Potocnik (1892–1929) described a space station in the geostationary orbit for meteorological observations. Later, in 1945, Arthur C. Clarke published his famous article on 'extraterrestrial relays' in the journal 'Wireless World', where he explained the advantages of geostationary satellites for communication. Many years later, Potocnik's and Clarke's vision became a reality, and the geostationary ring, which comprises all geostationary orbits suitable for practical use, is now one of the most important and most valuable regions in space.

Since the launch of Syncom-3 in 1964, more than 800 satellites and rocket upper stages have been put into GEO or its vicinity. Routine surveillance with ground-based radars and optical telescopes by the United States' Space Surveillance Network (SSN) is able to catalogue objects more than 1 m in size in GEO, providing orbital information (the NASA Two-Line Elements, or TLEs) as well as other characteristics such as the object's radar cross-section. At least one satellite and a rocket upper-stage have exploded in the geostationary ring, but the locations and spatial distributions of the fragments are unknown. The search for fragments in the geostationary ring and a better knowledge of the current debris population are of paramount importance in order to understand its future evolution, to assess the risk of collisions, and to define suitable and cost-efficient mitigation measures. Optical telescopes with 1 m apertures and equipped with a suitable CCD camera, such as ESA's 1 m Zeiss telescope at the Teide Observatory on Tenerife, have the ability to detect 10–20 cm sized objects in GEO.

CHARACTERISTICS OF THE GEOSTATIONARY ORBIT

The ideal geostationary orbit is circular, its orbital plane coincides with the equatorial plane, and its orbital period is one sidereal day (23 h 56 m 4 s). In practice, the orbits have a small eccentricity and inclination as a consequence of perturbations. Each satellite is usually assigned a longitude/latitude box, within which it has to stay, typically to within ± 0.1 deg for direct-TV satellites. For satellites serving mobile users, a larger latitude excursion is permitted, which may be more than 1 deg.

A geostationary satellite's orbit has to be adjusted periodically, otherwise it will leave its nominal station-keeping box because of perturbing accelerations due to:
- anomalies in the Earth's gravitational field
- gravitational effects of the Sun and Moon
- solar radiation pressure.

The longitude-dependent spherical harmonics associated with the Earth's gravity potential lead to resonance effects. The primary effect is a long-term perturbation of the semi-major axis, with a corresponding variation in longitude. The dominant longitude perturbation is a librational pendulum-like motion around the nearest stable point, at either 75° E or 105° W. The gravitational effects of the Sun and Moon and the oblateness of the Earth (J2) cause a precessional motion of the pole of the orbital plane with a period of about 53 years. An ideal geostationary orbit will reach an inclination of about 15 deg after about 26.5 years, which will decrease to zero after another 26.5 years. Solar radiation pressure induces a small eccentricity, which in turn leads to a radial variation, which in extreme cases may reach ± 75 km.

The geostationary ring is thus effectively a segment of a spherical shell of thickness 150 km and delimited by ± 15 deg in latitude (Fig. 1).

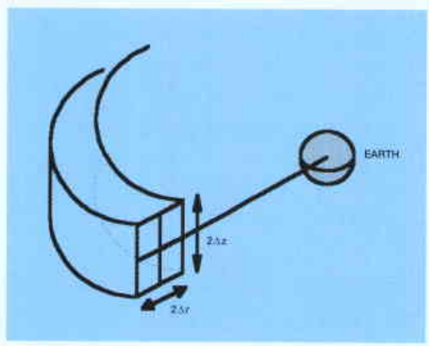

Figure 1. The geostationary ring

Current population of man-made objects in GEO

The usual way of putting a spacecraft into geostationary orbit is for the launcher to insert it into a Geostationary Transfer Orbit (GTO), from which it is then transferred using its own propulsion module to a near-geostationary orbit. This transfer may be accomplished with a single burn of a solid-propellant motor (Apogee Boost Motor, or ABM), or with a series of smaller burns if a liquid-fuelled motor is used. In many cases the ABM is separated from the spacecraft after the burn. The alternative is direct insertion of the spacecraft into a near-geostationary orbit by the launcher itself (examples being the Proton and Titan launch vehicles). In this case, the rocket's upper stage also ends up in near-geostationary orbit.

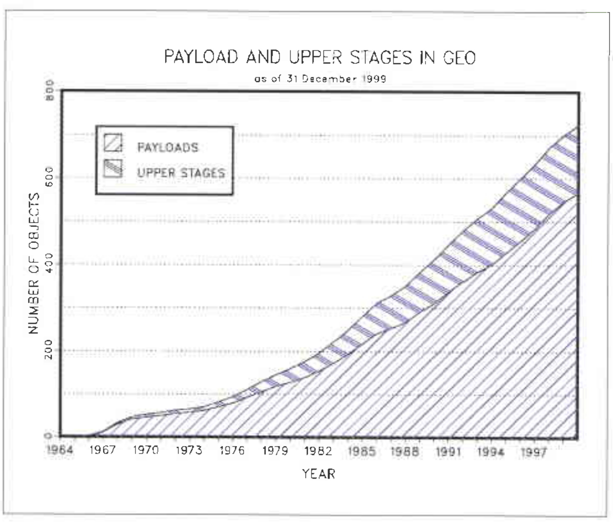

Figure 2. Time history of catalogued objects in GEO

Since 1989, NASA has provided ESA with the TLEs of all unclassified catalogued objects. These data are stored in ESA's Database and Information System for the Characterisation of Objects in Space (DISCOS). There are currently more than 840 satellites and rocket upper stages (rocket bodies, or RBs) in the geostationary ring and its vicinity. Figure 2 shows the time history of objects in the US SPACECOM catalogue (731 objects as of 31 Dec. 1999 in the DISCOS database). Another 111 objects are known to be in GEO, but their TLEs are not publicly available.

The 731 catalogued objects can be categorised as follows:

- operational spacecraft 242
- spacecraft in librational mode 115
- spacecraft/RBs in drifting mode 323
- TLEs not updated during the last 6 months 21
- indeterminate status 30

The true number of operational spacecraft exceeds 242, since classified objects are not included in the DISCOS database.

Spacecraft in librational mode are those that are no longer controlled and which, unfortunately, were not removed from the geostationary orbit at the end of their operational lifetimes. They follow an oscillatory motion around the nearest stable point (75° E or 105° W). In addition, the inclination of their orbits will vary cyclically between 0 and 15° with a period of about 53 years. Since they cross the equatorial plane twice per day, they constitute a collision hazard for operational spacecraft. At the maximum inclination of 15 deg, their relative velocity with respect to operational spacecraft is about 800 m/sec.

Geostationary satellites are thus at some risk of colliding with uncontrolled objects, particularly old geostationary satellites. In recent years, the practice has developed of transferring spacecraft at the end of their operational lives into a 'disposal orbit' above the geostationary ring. This simple but effective measure reduces significantly the risk of collision in GEO.

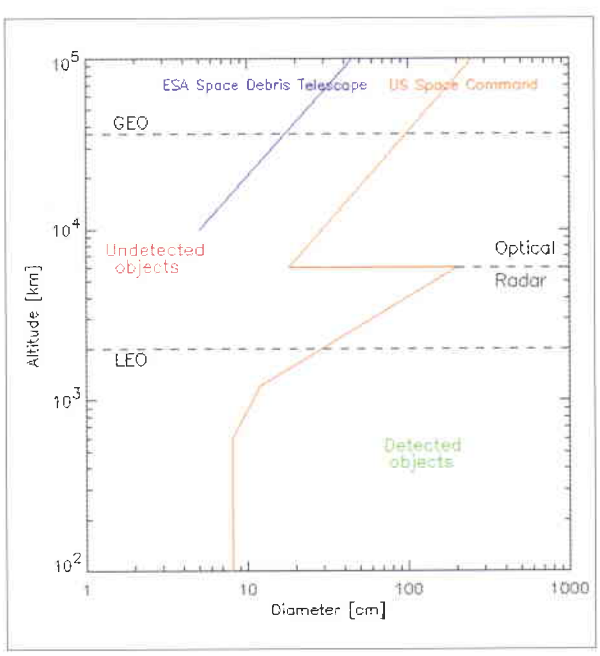

Figure. 4 Sensitivity of radars and optical sensors

An average of 25 – 30 new spacecraft are put into the geostationary ring every year (Fig. 3), a figure that is not expected to vary significantly in the coming years. Consequently, there are some 580 – 600 large debris objects (old spacecraft, separated ABMs and rocket bodies) in the geostationary ring and its vicinity. In addition, fragments from an exploding satellite (battery explosion on an Ekran spacecraft in 1978) and a rocket upper stage (Titan upper stage that launched the LES-8 spacecraft in 1968 fragmented in 1992) must also still be in GEO.

In 1996, ESA put a micro-debris and dust detector in the geostationary orbit on board the Russian Express-2 spacecraft at 80°E. The device, which is identical to the dust detectors flying on the Ulysses and Galileo spacecraft, detects sub-millimetre-sized objects which normally cause no significant hazard to operational spacecraft.

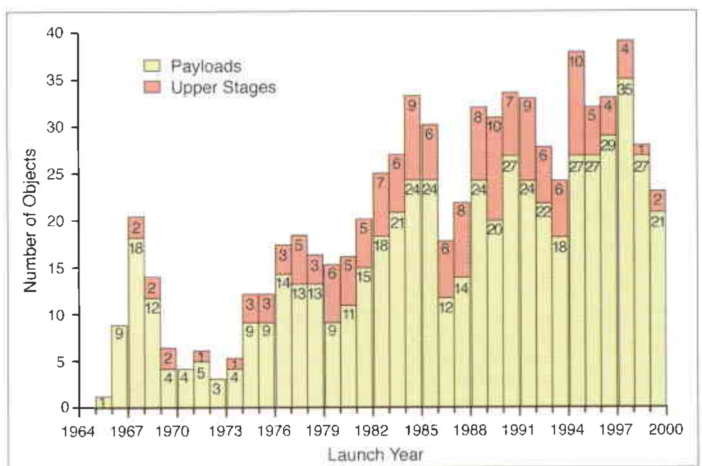

Figure 3. Annual launch rate into GEO

Space surveillance in GEO

Space surveillance involves detecting, tracking and determining the orbital parameters (e.g. the NASA Two-Line Elements) of orbiting objects. The United States Space Command regularly tracks and updates the parameters of about 10 000 objects orbiting the Earth. For lower altitudes, i.e. below a few thousand kilometres, powerful radars (classical dish radars and phased arrays) are used. For GEO, primarily optical telescopes with an aperture of 1 m are used (Ground-based Electro-Optical Deep Space Sensors), but some powerful radars can also track objects in the geostationary orbit. The minimum size of the objects routinely tracked in GEO is about 1 m (Fig. 4), but suitable telescopes have the sensitivity to detect sub-metre objects.

Optical observation is an efficient ground-based method of observing space debris at high altitudes, say 6000 km and above. At low altitudes, optical observations are less suitable because the object being observed must be illuminated by the Sun, while the observer must be in darkness. In the Low Earth Orbit (LEO) region, this condition can only be met for short periods at the beginning or end of a night.

The ESA Space-Debris Telescope

The ESA Space-Debris Telescope is installed in the Optical Ground Station (OGS) at the Teide Observatory on Tenerife, Canary Islands. The OGS was originally established by ESA in the framework of the Data Relay and Technology Mission for the in-orbit checkout of the payload of the Artemis spacecraft. The upgrading of the telescope for space-debris observations was initiated later. The Observatory is located on top of Izaña Mountain (2393 m), about 20 km northeast of Teide. The site has excellent seeing conditions, but light pollution from the densely populated coastal areas of Tenerife prevents optimum use of telescopes with mirrors larger than about 2 m. ESA's 1 m Zeiss telescope is unaffected by this problem.

The ESA Space-Debris Telescope is a classical astronomical telescope with a 1 m primary mirror and an English mount, which has two rotating axes, one being parallel to the Earth's rotation axis. For sidereal tracking, rotation is only needed around one axis. Another advantage is that for an instrument mounted on the telescope, the field of view is not rotating whilst the telescope is tracking the sky.

The telescope has two different focus configurations: Ritchey-Chrétien and Coudé. The space-debris system uses a modified Ritchey-Chrétien configuration. Its field of view has been increased to 1° with a new secondary mirror and a set of lenses to reduce the focal length to 4.47 m. A large field of view is essential for an efficient debris search (Fig. 6).

Figure 5. The Optical Ground Station at the Teide Observatory

The telescope is equipped with a large-array CCD camera. The array consists of a mosaic of four 2048 x 2048 pixel detectors, which form a 4096 x 4096 pixel-square device. At the space-debris focus, one pixel covers a field of view of 0.6 arcsec. The total field of view of the device is about 0.7° x 0.7°. The CCDs are cooled with nitrogen to 160 K to reduce the dark signal produced by thermal motion. The detectors and the preamplifiers are located in a vacuum chamber and are thermally connected to a cryostat chamber filled with liquid nitrogen. To ensure a constant operating temperature, the detectors are also electrically heated.

Together with the large field of view, a short image readout time is essential for space-debris observations. Each CCD chip is therefore equipped with two readout channels and is controlled by a separate amplification

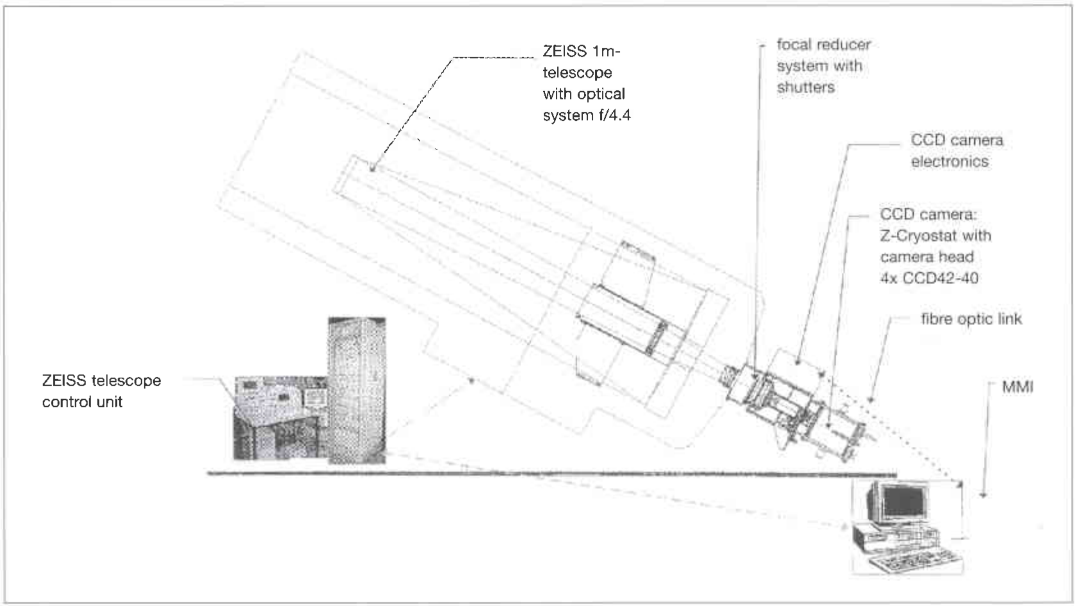

Figure 6. Telescope configuration for space-debris observation

and digitisation unit. The units are read out in parallel. The shortest readout time for a full image is 19 s, with a readout noise level of 4–6 electrons per pixel. This allows the detection of 20–21 magnitude objects with 1–2 s exposure times. For debris in GEO, this roughly translates into objects with diameters of 20–10 cm.

The upgrading of the optical system and the design and development of the 4 k x 4 k CCD camera were carried out by Carl Zeiss GmbH (Jena) and SIRA Ltd. (Chislehurst/London). The software for observation planning, data acquisition and processing was developed by the Astronomical Institute at the University of Bern (CH) and the Astrophysical Institute of the Canary Islands (IAC).

Observation control

The space-debris observations require accurate coordination of the telescope motion and image acquisition. The main control of the observations is assigned to the Central Control Computer (CCC), a Sun SparcStation 20, which directly controls the camera. The telescope is controlled by the Telescope Control Computer (TCC), which receives pointing commands from the CCC via a serial link. The TCC computes the atmospheric-refraction and pointing corrections.

For accurate telescope pointing, a so-called 'pointing model' must be established, which relates the pointing direction of the optical axis with the reading of the angular encoders of the mount. It must include terms for the non-perpendicularity of the telescope axes, the periodic errors of the angular encoders, as well as terms for the changing mechanical bending of the telescope at different positions. The parameters of the pointing model are determined by observing catalogued stars with known positions. The pointing corrections derived from the model are applied each time (every 100 ms) when updated pointing values are calculated. The resulting pointing accuracy for any position on the sky is better than 10 arcsec, while the tracking error is less than 2 arcsec per hour.

The accurate timing of the observations is important for the orbit determination. The system clock in the TCC is driven by a GPS receiver. The shutter can be commanded with an accuracy of better than 1 ms.

During the observations, 2–3 images per minute are acquired. The telescope is re-pointed between each exposure and the acquired data stored. Clearly, these tasks cannot be performed manually, especially over several hours, and so the CCC executes them automatically according to a predetermined observation plan. The progress of the observations can be followed from messages on the screens of the CCC, where each acquired image can also be displayed.

Observation planning

For both short- and long-term observations, a special planning tool is available in the OPC. It allows the planning of: surveys, follow-up observations for newly discovered objects, and calibration measurements for the telescope and camera, and creates an observation-plan file for the CCC's central controller.

Currently, observations are focussing on objects in GEO and GTO. These objects, especially those in GEO, are stationary or slow-moving with respect to an Earth-fixed frame. To optimise the signal-to-noise ratio for objects of interest, we track them during the exposures.

The detection technique is based on an algorithm comparing several consecutive frames of the same field in the sky. Fixed background stars are identified on a series of 10 to 30 frames, and the remaining parts of the frames are scanned for any additional objects. The telescope is therefore moved after each exposure so that the same area of the sky is passing the field of view at the next exposure (Fig. 7). With this method, the telescope slowly scans the sky from east to west whilst it is following the stars.

The exposure frequency has to be selected so that any object detected will be visible in three consecutive frames. Given this three-fold-coverage requirement, the current set-up allows one to observe up to three different

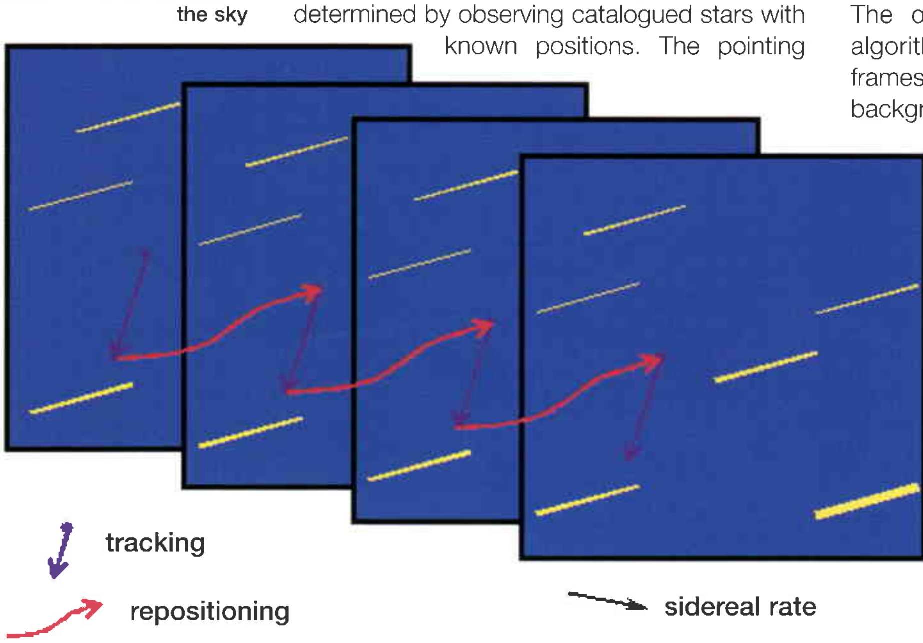

Figure 7. Tracking scenario for surveys. The telescope tracks the object during the exposure and is then repositioned between exposures to always observe the same field in the sky

nearby areas of the sky in parallel. The 2 – 3 parallel fields are selected to be adjacent fields of view in the north-south direction. This approach maximises the observable area.

During the tracking of known objects, the 're-pointing to the same sky position' scenario is followed, so that the image analysis method does not need to be changed. However, instead of stopping the telescope, it follows the object during the exposure in order to collect more photons at the same position on the CCD, thereby improving the signal-to-noise ratio for that object.

Data analysis

The data analysis is performed in quasi-real-time on the OPC. The offline data-processing system is controlled through a user-friendly interface (Fig. 8). This tool allows autonomous interactive processing of the available data using Processing Unit Lists (PULs), which combine several elementary tasks, such as calibration of the camera and the telescope and analysis of the debris observations. In normal observations, the data processing is largely carried out in an automated mode. The processing begins once the first set of frames has been stored and the log file from the observations becomes available.

The search procedure for unknown objects is based on a 'masking technique' (Fig. 9), whereby the known objects (e.g. stars) in the frame are masked, so that those still visible are the unknown ones. The first step is to generate a median frame from the entire series of observations. This allows one to eliminate objects that do not appear on the majority of the frames at the same position (e.g. moving objects, cosmic-ray events, etc.). Another processing unit generates the mask from the median frame.

A cosmic-ray detection filter marks the corresponding objects accordingly (cosmic-ray events are discriminated by virtue of the shape of the intensity profile). Since the search procedure is operating at the level of single frames only, it is necessary to correlate the detected objects from the individual frames. This is achieved using mean-motion criteria (upper and lower bound for expected mean motion). The result is a list of objects found in more than one frame, as well as individual lists of objects found in single frames only. Objects found in several frames are given a working name and designated as moving objects.

When an object is detected, its sky position is calculated using catalogued stars in the image as a reference. Its orbit can be determined by analysing consecutive frames. If the object is detected for the first time, only 2 - 4 observed positions will be available. The epoch difference between consecutive positions is about 1 min, which is not sufficient to determine the orbit accurately. Therefore as a first approximation a circular orbit is assumed, and this is then improved with the new data when the object is re-observed.

Results of the observations

A first, very limited series of preliminary system

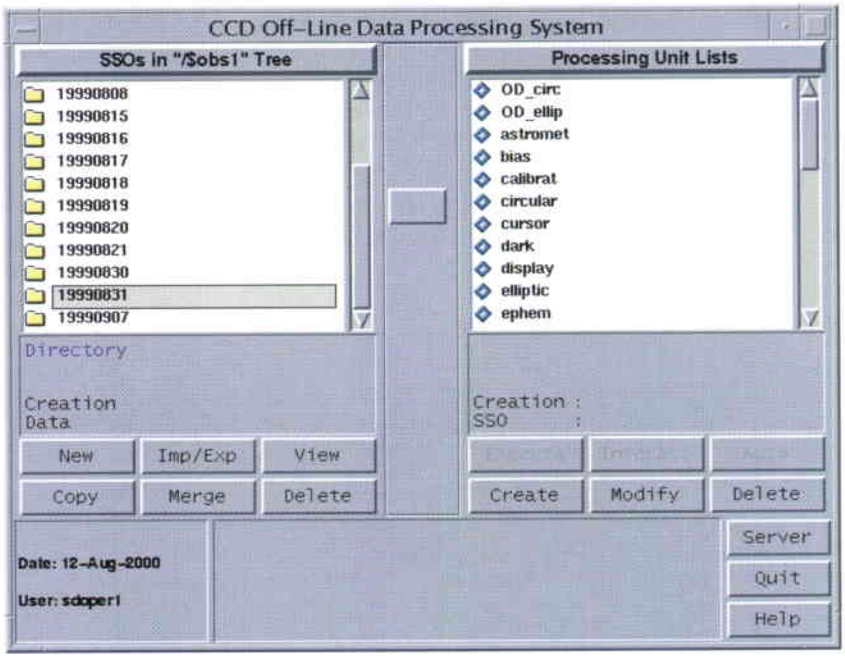

Figure 8. The main window of the offline data-processing system

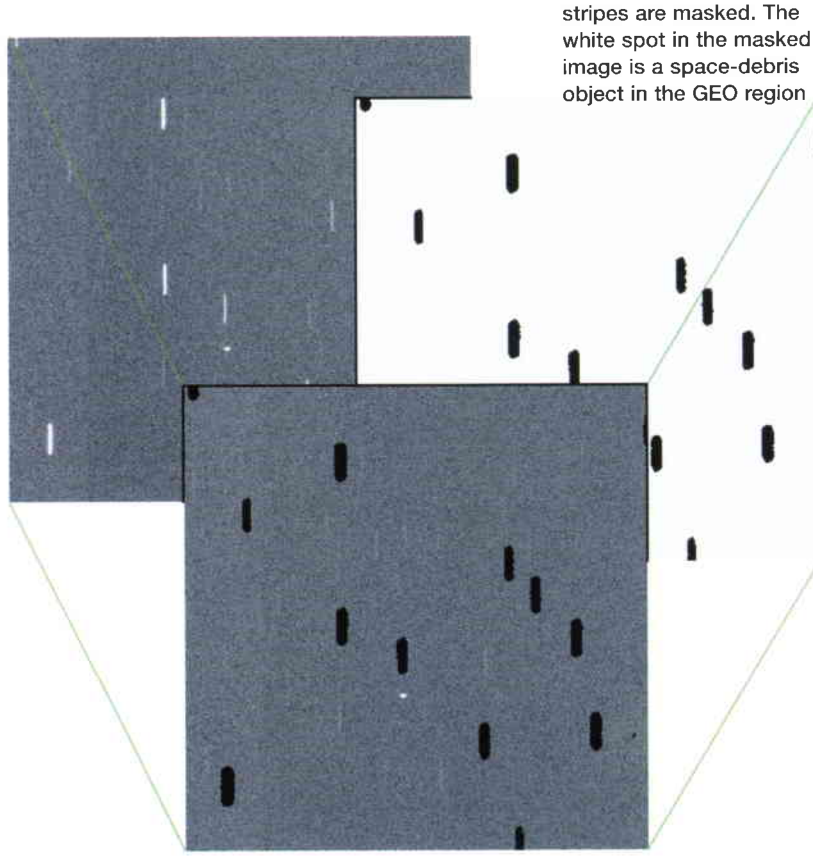

Figure 9. A sub-image (top left) is taken from the observation frame together with the generated mask (top right). In the bottom image the original image is displayed after the masking. The stars form stripes because the telescope pointing is Earth-fixed during exposure; these stripes are masked. The white spot in the masked image is a space-debris object in the GEO region

tests with the ESA 1 m telescope was performed between July and September 1999. The campaign lasted for 13 nights, with a total observing time of 49 hours (Table 1). The observation directions were chosen such that GEO objects were optimally illuminated by the Sun, which implies a direction near the Earth's shadow cone. All frames were exposed for 2 s and the series arranged so that a GEO object would appear on average in three consecutive frames.

Table 1. Observation statistics for the autumn 1999 test campaign

	Surveys		Follow-ups
Number of series	100		102
Number of frames	5439		1034
Scanned area		895 deg^2	
Total observing time		49 hours	
Total image data		52 GB	

The observation scenario consisted of survey series interrupted by follow-up observations for uncorrelated objects (UCOs = objects not listed in the US SpaceCom Catalogue). The latter were scheduled using orbit information from the on-line processing. Figure 10 shows the distribution of the fields searched, as seen in the horizon system from Tenerife. The survey was not homogeneous, either in terms of sampled longitude/latitude space, or in orbital element space (we were most interested in objects on 'high-inclination' orbits). All observation series were analysed on-line. The process identified 360 single detections of correlated, and 696 detections of uncorrelated objects. An off-line correlation over all series for all nights using orbit determination revealed 56 correlated and 150 uncorrelated objects.

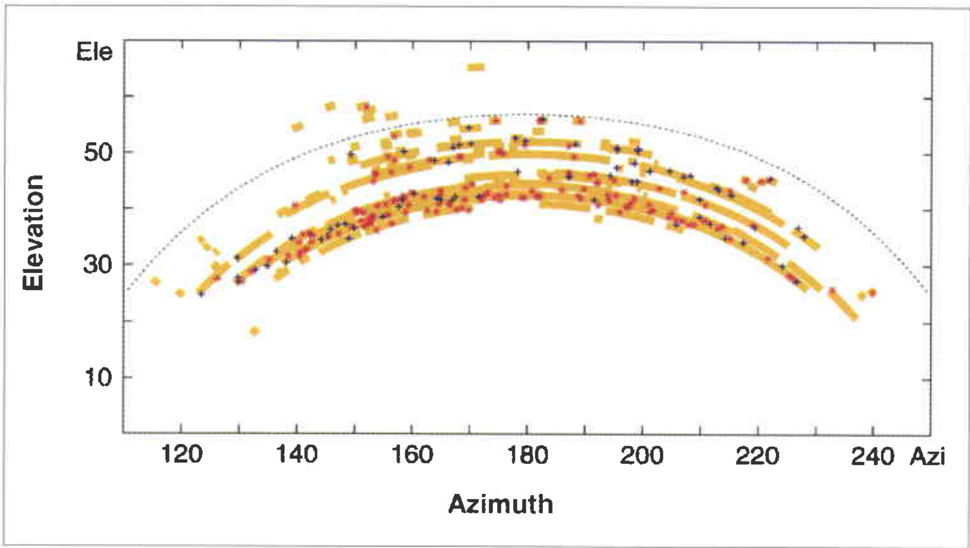

Figure 10. Search fields of the autumn 1999 test campaign. The dashed line indicates the location of the GEO ring as seen from Tenerife, crosses indicate detections of correlated objects, and asterisks indicate detections of uncorrelated objects

Brightness distribution
The magnitude distribution of the detected correlated and uncorrelated objects is shown in Figure 12. The solid line shows the instrument sensitivity as determined from independent calibration observations. The distribution is bimodal with the correlated objects clustered around magnitude 12.5, and a large population of uncorrelated objects in the range from magnitude 15 to 21. There are a few bright objects that did not correlate with the available catalogue, most likely due to poor quality of the corresponding elements in the catalogue (e.g. objects that had recently been manoeuvred). In addition, some objects were not contained in the reference catalogue.

It is important to note that the decrease in number of objects fainter than magnitude 18 is due entirely to the limiting magnitude of the observation system. The luminosity function beyond magnitude 18 could therefore still increase! In all likelihood, the UCOs with magnitudes above 16 are mission-related objects and fragments of breakups.

Inclination distribution
Figure 13 shows the distribution of inclinations of all observed objects. It is important to realise that the observed distribution is not the real distribution of the population, but merely reflects the selection of the survey fields. When surveying a field at a given declination, we can only find objects with inclinations greater than or equal to the absolute value of this declination. The correlation between the distribution of the observation time per declination bin given in Figure 14 and the distribution in Figure 13 is obvious.

RA of ascending-node distribution
The distribution of the orbital elements, in particular that of the inclination as a function of

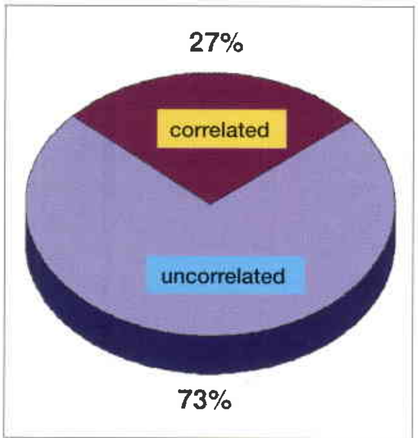

Figure 11. Percentages of catalogued and unknown objects detected by the survey

the right ascension of the ascending node (Fig. 15), may provide some indications concerning the potential sources of debris objects.

The well-known structure observed in Figure 15 is caused by the precession of the orbital planes, due to the Earth's oblateness and luni-solar perturbations. There are, however, uncorrelated objects in unexpected regions, e.g. at high inclinations for ascending nodes between 100° and 150°. A more detailed interpretation of this figure is difficult because of the very inhomogeneous sampling of the orbital element space by the observations. Apparent 'clumping' (e.g. at 30 deg ascending node and 16 deg inclination) may be a pure observational selection effect.

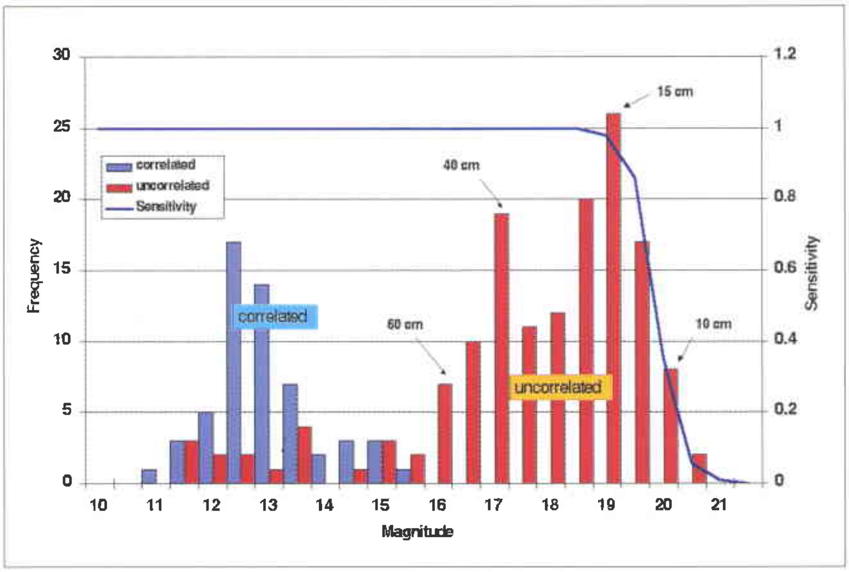

Figure 12. Magnitude distribution of correlated and uncorrelated objects. The solid line shows the instrument sensitivity as determined from independent calibration observations

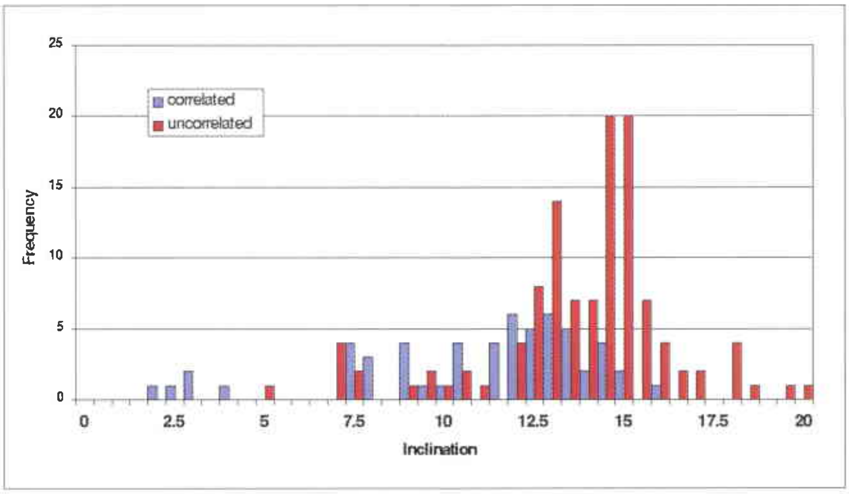

Figure 13. Distribution of inclinations

Conclusions

The population of anthropogenic objects in the geostationary ring is steadily increasing. There is no natural cleaning mechanism, such as air-drag, which removes objects from the ring. Objects therefore remain in this region, carrying out complicated motion patterns with periodicities ranging from 1 day to about 53 years.

About 250–270 satellites in GEO are controlled, but more than 100 have been left there at their end-of-life rather than being transferred to a 'disposal orbit'. The latter constitute a hazard for operational spacecraft in GEO and are therefore a burden for the future. To reduce the collision hazard for the operational spacecraft, they should have been transferred to a disposal orbit above the geostationary ring at the end of their operational lifetimes. Unfortunately, the recommendations of IAA, ITU and IADC for the

THE INTER-AGENCY SPACE-DEBRIS COORDINATION COMMITTEE (IADC)

The Inter-Agency Space-Debris Coordination Committee (IADC) currently has eleven members: ESA, NASA, the Russian Aviation and Space Agency (Rosaviakosmos), Japan, ASI (Italy), BNSC (United Kingdom), CNES (France), the Chinese National Space Administration (CNSA), DLR (Germany), ISRO (India) and the National Space Agency of the Ukraine (NSAU).

IADC was founded 1993 in Darmstadt (Germany) on the occasion of the First European Conference on Space Debris. The Committee is concerned with all technical issues associated with space debris. Its main objectives are to exchange the results of existing research, to cooperate in new research activities, and to identify and recommend debris mitigation options. The IADC comprises a Steering Group and four Working Groups: WG1 Measurements; WG2 Environment and Data Base; WG3 Protection; and WG4 Mitigation. It also provides technical support to the deliberations on space debris at the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS).

The 19th IADC Meeting, scheduled for 22 - 23 March 2001, will be hosted by DLR, in Cologne, Germany.

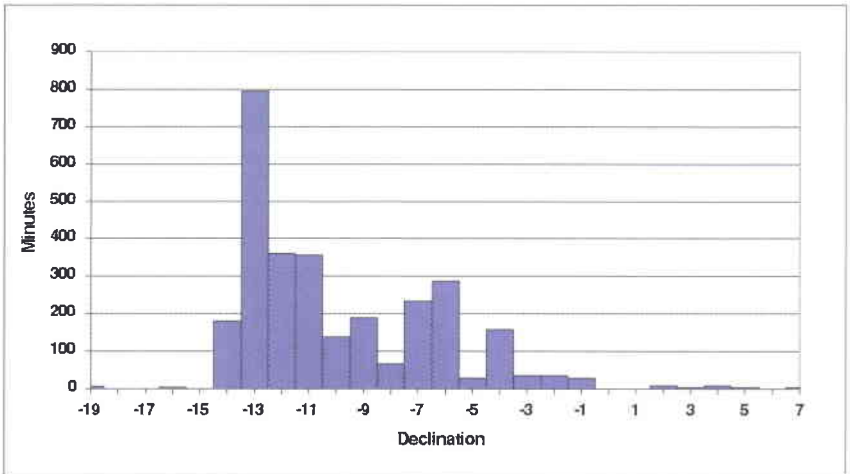

Figure 14. Observation time per declination bin

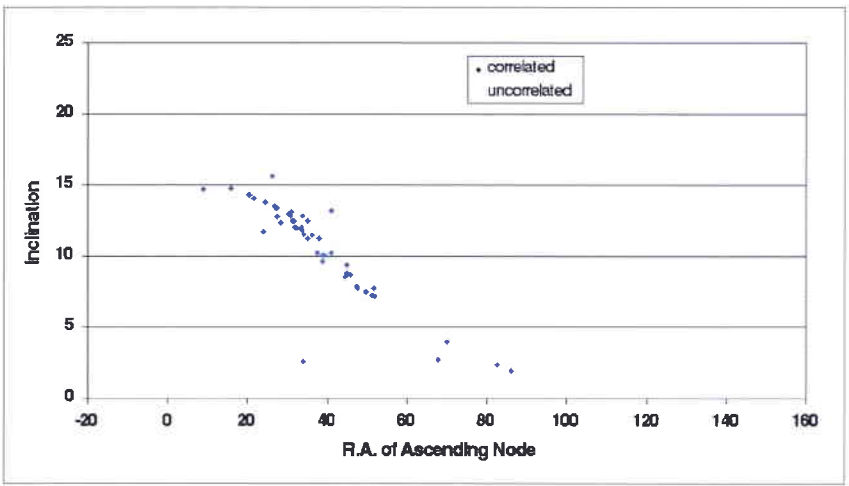

Figure 15. Distribution of inclinations as a function of right ascension of ascending node

re-orbiting of geostationary satellites at end-of-life are only vaguely followed by spacecraft operators. In order to keep the risk of collisions in the geostationary ring within acceptable limits, a code of conduct or some regulation would be beneficial.

Preliminary observations with ESA's Zeiss telescope in Tenerife have shown that there is a significant population of small-debris objects in the 10 – 100 cm size range in the geostationary ring. Extrapolations indicate an uncatalogued population of about 1600 debris objects between 10–15 cm and 1 m in size in GEO. The only plausible source for this debris population is breakups of spacecraft, ABMs and rocket upper stages. These objects will remain indefinitely in the GEO region and therefore constitute a real safety hazard for operational spacecraft.

ESA is now in a position to monitor independently objects in about one third of the geostationary ring. The next step will focus on the Geostationary Transfer Orbit (GTO) region.

Acknowledgement

The efficient support and expertise in computer matters of Santiago Llorente (ESOC) is gratefully acknowledged.

THE GRAVEYARD FOR DECOMMISSIONED GEOSTATIONARY SATELLITES

Collisions between decommissioned spacecraft and operational spacecraft in GEO can easily be avoided by transferring the spacecraft at end-of-life into a disposal orbit. Because of potential radio interference and satellites in GTO space, the disposal orbit should be located above the geostationary ring. The costs of the altitude increase can be formulated in terms of the velocity increment of 3.64 m/sec required for every 100 km increase in semi-major axis.

Recommendations concerning the minimum altitude of the disposal orbit have been issued by the International Academy of Astronautics (IAA), the International Telecommunications Union (ITU), and the Inter-Agency Space Debris Coordination Committee (IADC). Both the IAA Position Paper and the ITU Recommendation ITU-R S.1003 stipulate a minimum re-boost altitude of 300 km or more. The IADC recommends that the minimum perigee altitude min ΔH (in km) above the geostationary altitude of 35 786 km should be not less than

$$\min \Delta H = 235 \text{ km} + Cr \times 1000 \times A/M$$

where Cr is a coefficient between 0 and 2, A is the cross-sectional area (m^2), and M the spacecraft mass (kg). The perigee increase should be executed as a multi-burn series of manoeuvres, to minimise the probability that errors in estimating the residual propellant will leave the spacecraft in a GEO-crossing orbit.

The IADC recommends that when relocated to the super-synchronous disposal region, the spacecraft should be depleted of all other sources of stored energy, pressurant gases, battery energy, etc. in order to avoid accidental explosions and the ejection of debris back into GEO. Unfortunately, many operators ignore the IAA, ITU and IADC recommendations. About 40 geostationary spacecraft have been retired from service during the last two years; about one third of them were properly disposed of, while two thirds were either left in geostationary orbit or their orbital altitude was increased by an insufficient amount.

EAC Training and Medical Support for International Space Station Astronauts

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The operation of the International Space Station (ISS) will be a global multilateral endeavour. Each International Partner will be responsible for the operation of its elements and for providing a crew complement proportional to its share of the overall resources. The preparations of the European Astronaut Centre to furnish training and medical support for the ISS astronauts are described.

Introduction

The role of the European Astronaut Centre (EAC) in ESA's contribution to International Space Station (ISS) operations will be two-fold:

- training all ISS astronauts on ESA flight elements and payloads;
- providing ESA astronauts for international crews, proportional to the ESA share of the overall resources, including their support, in particular their medical surveillance and health care.

The training of ISS astronauts follows a distributed concept laid down in the Memorandum of Understanding on International Space Station Cooperation between ESA and NASA. Each International Partner will train all ISS astronauts on its flight elements and payloads. ESA is therefore responsible for the training on the operation and maintenance of the Columbus systems, the crew interaction with the Automated Transfer Vehicle (ATV) and the operation and maintenance of all ESA payloads.

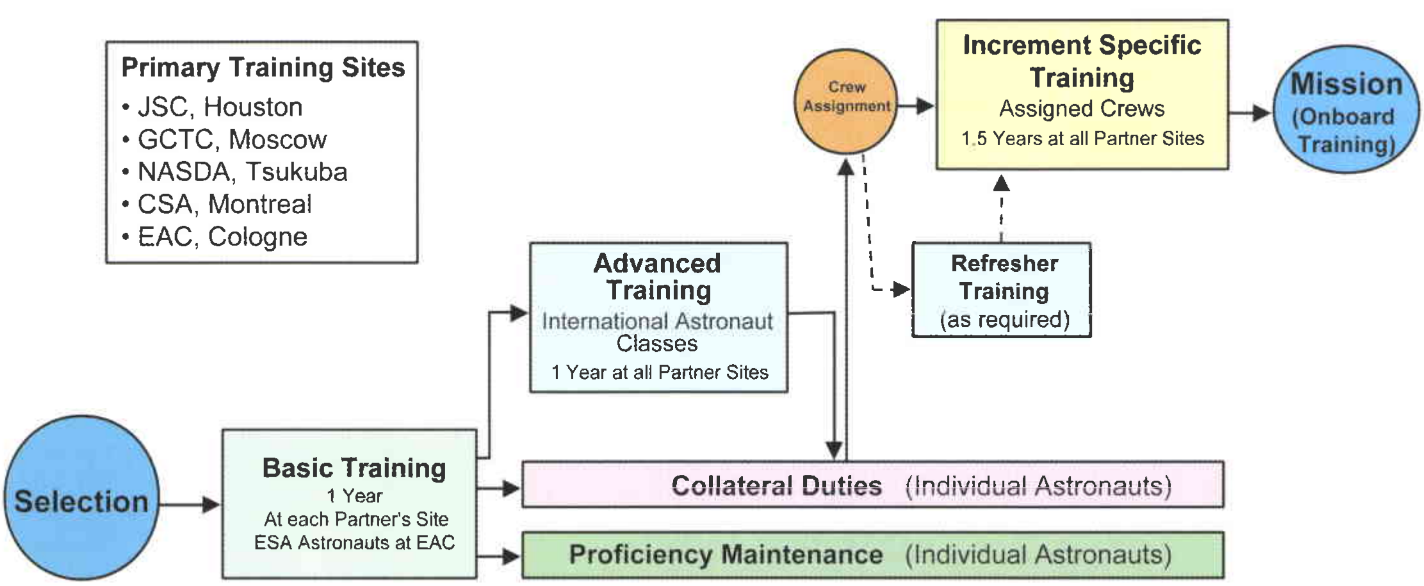
The ISS requires continuous human occupancy via long-duration missions. Ensuring the health and wellbeing of astronauts and optimising their performance throughout all mission phases are the joint responsibilities of the medical support offices of each International Partner contributing crew members.

ISS training flow

Training develops the astronaut's knowledge, skills and attitude in order to perform specific tasks. The training of ISS astronauts is performed in three phases (Fig.1), leading to mission readiness:

- Basic Training;
- Advanced Training;
- Increment Specific Training.

Figure 1. ISS astronaut training flow



As the first training phase following selection, *Basic Training* lasting up to a year provides the candidate astronauts with basic knowledge on space technology and science, basic medical skills and basic skills for operational work with Station systems and payloads. These include special capabilities such as diving as the basis for extra-vehicular activity (EVA) training. Basic Training is given by each International Partner to its own candidate classes.

Advanced Training provides Station crews with knowledge and skills related to operation of the Station elements, payloads, transport vehicles and interaction with the ground. Building on Basic Training, it is generic and does not yet focus on specific onboard tasks and procedures. It is job-orientated, concentrating on the tasks and systems knowledge associated with a single job involving one or more students. Station crew members become familiar with all systems and specialise in a subset of functions, such as resource and data operations, robotics, navigation, maintenance, intra- and extra-vehicular activities, medical aspects and payload operations for long-term on-orbit payloads. It is given to international classes of astronauts from all the Partners and takes place at all Partners' facilities to provide first-hand familiarity with Partner flight elements and operations. Training on Columbus systems, payloads and ATV is carried out at EAC for all ISS astronauts. On successful completion of the year-long Advanced Training, an astronaut is eligible for assignment to an 'increment' crew (see below).

Increment Specific Training (an 'increment' is the period between crew exchange aboard the Station) provides an assigned Station crew (and backup crew, if applicable) with the knowledge and skills required for the planned and contingency onboard tasks of the increment. The crew trains together as much as possible in order to foster team integration and spirit. Increment Specific Training lasts about 1.5 years, including several weeks at EAC covering Columbus systems, payloads and ATV.

Increment Specific Training comprises *Multi-Segment Training* during the last 6 months, which combines payload and systems operations for the entire Station. The crew works as a team, sometimes with ground controllers via integrated simulations. This training takes place at NASA's Johnson Space Center (JSC) in Houston, Texas, USA, except for Soyuz-launched crews, whose final 6-12 weeks are spent at the Gagarin Cosmonaut Training Centre, Star City, Russia.

On-Board Training helps crews to retain their proficiencies from ground training or to learn new tasks 'just-in-time' on a case-by-case basis. This limits the need for extensive pre-flight training on all aspects of a particular job and makes the overall training period shorter and more effective.

Proficiency Maintenance periodically refreshes special skills such as robotic manipulation and rendezvous and docking operations. The maintenance of basic capabilities in piloting and physical fitness is also covered.

Each astronaut passes through Basic Training and Advanced Training only once. As there can be a considerable gap before mission assignment, *Refresher and On-the-job Training* can be required before specific areas of Increment Specific Training.

In parallel with their training – as time allows and between training phases – astronauts are assigned to *Collateral Duties*. They work in technical areas such as future missions or in support of development programmes, emphasising crew operations, man-machine interfaces and crew safety. Here, a specialisation is often acquired that is relevant for crew selection for an ISS increment mission.

Space Station training challenges

The ISS operational set-up creates specific challenges for training preparation and implementation. The global distribution of training requires a balance between training at the various Partner sites and the time spent travelling between them. The advantage of the distributed training is the proximity to the origin of expertise – the close availability of experts for systems and payload aspects as well as of scientific institutions and investigators. The distribution of the overall training time – an important Station resource – is critical.

ISS onboard operations differ from the timeline-driven approach of relatively brief Shuttle and Spacelab missions. Long missions are more akin to laboratory-type operations on Earth. For ESA, participation in long Mir missions such as Euromir-95 was very important in understanding the different style of operations. The general trend of ISS training is away from procedure- and timeline-driven training and towards an emphasis on basic skills and knowledge.

Another challenge is the fact that the training cycles for different increments overlap and require continuous schedule updating and courseware evolution. This requires very complex configuration management, particularly for the training facilities.

A possible solution for meeting the specific ISS training challenges is to focus on Advanced Training, which takes place before crew assignment. This phase is less time-critical because it is performed only once per astronaut. Another is to reduce classroom sessions and focus on workbook self-study as well as, eventually, on computer-based training.

Some training will be on-the-job. Many procedures cannot be learned on the ground because of time limitations. This applies in particular to corrective maintenance that is infrequent and not safety-critical – those procedures can be learned onboard 'just-in-time'. Onboard refresher training will be performed as needed, efficiently supported by onboard documentation. The on-orbit hand-over is also important, when the departing crew tutors the new arrivals on the Station's status.

Multilateral training cooperation

The ground rules for the Partner contributions to overall ISS operations are laid down in the Intergovernmental Agreement (IGA) and the Memoranda of Understanding (MOUs). Each Partner provides Basic Training for its own astronauts, and training specific to its flight elements and payloads for all ISS astronauts. Multi-segment and integrated ISS training are common responsibilities. NASA provides training integration and coordination.

The overall decision-making body is the International Training Control Board (ITCB). It delegates Systems Training matters to the Operations Training Panel, and Payload Training matters to the Payload Training Panel. The ESA training organisation covers Systems Training, Payload Training and Instructor Training, as well as Basic Training and Special Skills Training. The Ground Personnel Training is distributed among the respective Control Centres. For ESA, the ATV Control Centre in Toulouse (F) takes care of the ATV Ground Personnel Training, while the Columbus Control Centre in Oberpfaffenhofen (D) is responsible for the Columbus Ground Personnel Training. At present, ITCB members meet about once a year (Fig. 2) and have monthly teleconferences. After ISS assembly is complete, the meeting frequency will substantially increase.

Training preparation

EAC's preparation for training follows the instructional development approach. It starts by analysing crew tasks and creating a course-level Training Catalogue, which defines tasks, objectives, media and tools. The next step is the training design, which is contracted to an

Figure 2. The International Training Control Board at its most recent meeting, at EAC in May 2000

external company or consortium. An industrial team is typically composed of flight element or payload manufacturers, training experts and payload user centres. The output is a lesson-level Training Catalogue, which defines lesson plans, instructor requirements, evaluation criteria, resources and planning. This catalogue is the input to the next phase, the training development, which is also usually contracted to an industrial group. During this phase, the training material is produced: training manuals, workbooks, presentation material, evaluation tools, simulation scripts and computer-based training. This phase includes instructor selection and training, and concludes with the first training cycle and training evaluation.

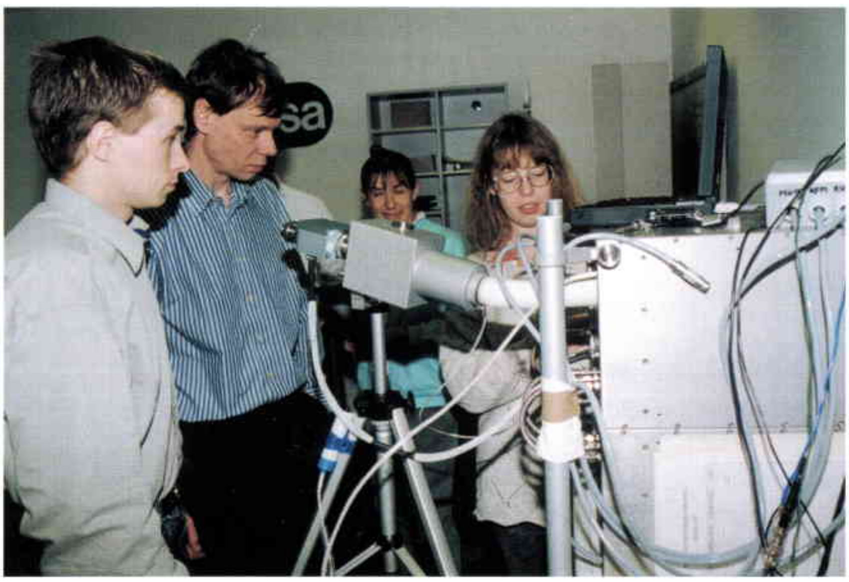


Figure 3. Training at EAC on the Respiratory Monitoring System

Instructors, who are already closely involved in the training development phase, are selected from experts in industry and user centres. They should already be subject matter experts in their respective fields of training. They receive basic Instructor Training to become familiar with the overall ISS programme and the instructional development process. A small core team of full-time instructors at EAC is planned, supported by part-time instructors from industry, user centres and scientific institutions coming in as required. For experiment-specific training, the respective Principal Investigators will be invited to provide training with first-hand expertise. It is obvious that astronaut travel time for training and medical baseline data collection (for comparison with flight data) must be minimised.

The certification process plans formal examinations in addition to structured and standardised assessment by instructors. This applies to the basic, advanced and increment-specific training.

A detailed training evaluation process will be applied through the various phases of training preparation analysis, design and development. The training development will be concluded by pilot courses and, finally, the Training Readiness Review. Training implementation and crew performance will be evaluated during training and the mission. Appropriate feedback to the training process will be identified.

Payload training at EAC for the Euromir missions (Fig. 3) was an important opportunity to gain first-hand experience with the specific aspects of long-duration missions.

Training facilities

Training (Fig. 4) for ESA elements and payloads is concentrated at EAC, where there is an office building, a training hall and a 10 m-deep 12 mx10 m Neutral Buoyancy Facility. The training hall will accommodate a Columbus Trainer with high-fidelity man-machine interface, a Columbus Maintenance Mockup for mechanical maintenance, an ATV Mockup for cargo handling and an ATV Rendezvous and Docking Simulator. For each facility-class payload, there will be a high-fidelity Payload Training Module. Additional facilities will be a Columbus Data Management System Part Task Trainer, Computer Based Training Facilities, classrooms, Medical Training Facilities and Fitness Facilities. The Astronaut Training Data Base is a central development and planning tool. Of course, this set-up requires an advanced communications and data-handling infrastructure. ESA will also support multi-segment training at JSC and provide a Columbus Trainer with reduced fidelity (with respect to the payloads) for integration into the ISS Training Facility. At the Gagarin Cosmonaut Training Centre (TsPK) in Moscow there will be European Robotic Arm (ERA) Training Facilities provided by ESA and operated by TsPK. An ATV Rendezvous and Docking Simulator is also planned.

Training preparation schedule

According to the ISS assembly sequence (Revision F), Columbus will be launched in October 2004 and the first ATV in April 2004. The first ESA Advanced Training will begin about 2 years before Columbus is launched, and the first ESA Increment Specific Training will be carried out starting about a year before Columbus. According to this schedule (Fig. 5), the Training Readiness Review will be in September 2002. The Columbus Training Facility development is underway: the critical design review was recently concluded and the Facility's delivery at EAC will be end-2001 for the acceptance at the beginning of 2002.

Medical support activities

Ensuring the health and wellbeing of astronauts

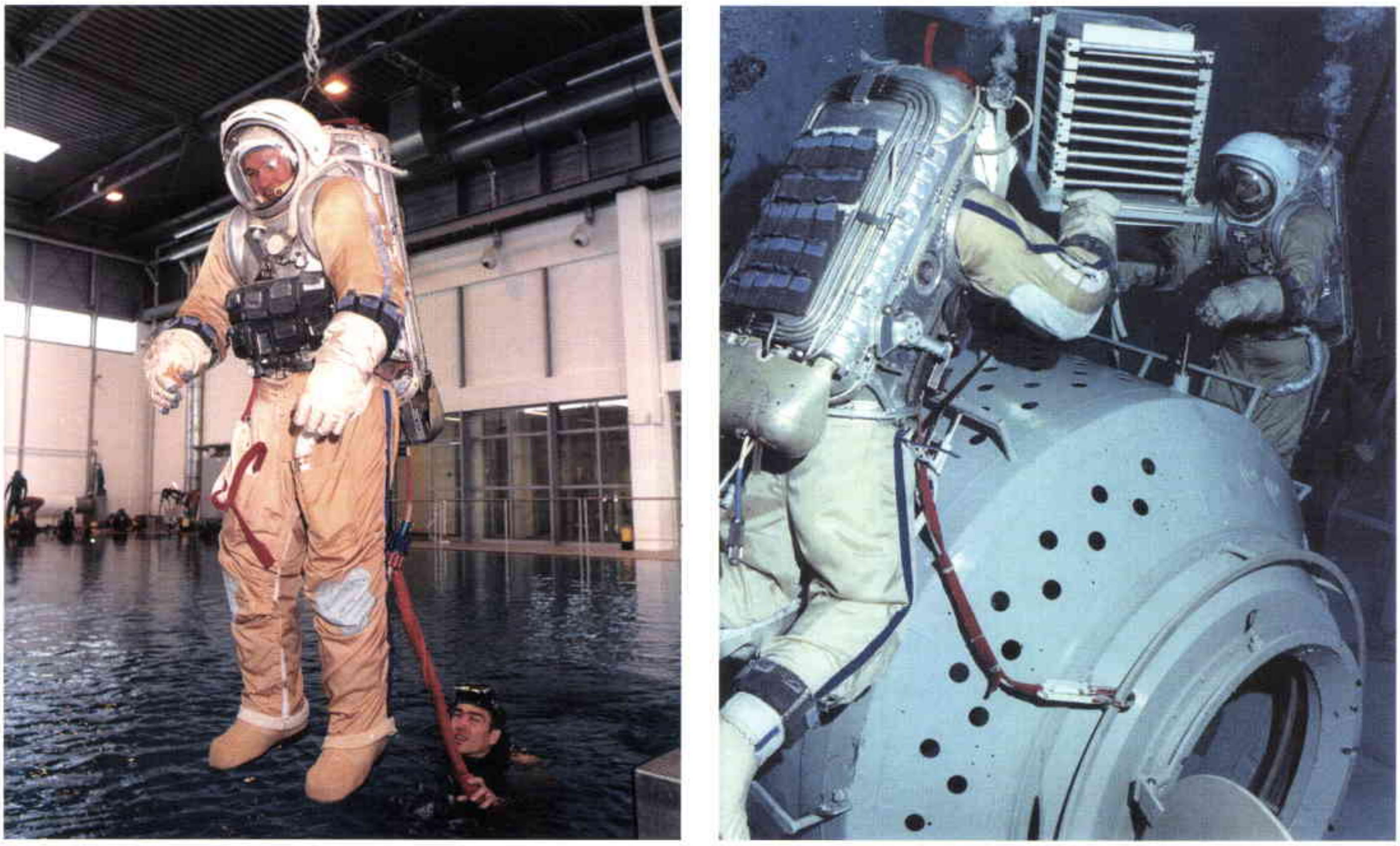


Figure 4. EVA training in EAC's Neutral Buoyancy Facility

Figure 5. EAC training development schedule

– the most valuable resource aboard a spacecraft – is a prime responsibility of the Agency. The World Health Organisation defines health *"as a state of complete physical, mental, and social wellbeing and not merely the absence of disease or infirmity"*. In order to meet the requirement to maintain the health, fitness and wellbeing of its astronauts, the ESA/EAC Crew Medical Support Office provides a wide spectrum of services.

Figure 6. Thomas Reiter exercising aboard Mir

It is responsible for the medical aspects of astronaut selection and annual medical recertifications, as well as providing general medical care, medical intervention for diagnosis and treatment of illness and injury, and emergency medical services to astronauts and their dependants. It also represents the medical interests of the crew and astronauts in policy-making decisions, requirement development, issue resolution and interfaces with ESA internal and external medical organisations.

In order to minimise undesirable health consequences and to enable a healthy and productive crew to accomplish mission goals, a programme of comprehensive health care in all mission phases is provided to the astronauts at their EAC home base and other locations, such as ESTEC and JSC. This programme includes individually-tailored fitness regimes, nutritional advice and psychosocial support to crew and their dependants. During a mission (Fig.6), the programme continues with specific fitness and countermeasure activities, and periodic health and fitness evaluations. In addition, there is a 'human behaviour and performance support programme' designed specifically for long-duration stays aboard the Station. It covers individual psychological support packages, family conferences, crew resource management, crew support items, habitability and multicultural aspects.

The space environment requires high dependence on technical means to maintain life. Since system failures potentially affect crew health, expertise in environmental health is required. Specific areas of concern to the medical office are breathable atmosphere, drinking water, contact surface cleanliness, lighting, noise and vibration exposure, radiation exposure, hygiene, habitability and microgravity.

Life sciences research aboard the ISS is of high interest to the scientific community. According to international regulations, experiments on human test subjects have to follow certain formal and legal requirements, involving ethical and medical boards to review and approve such scientific research. The medical office provides the executive secretary to the ESA Medical Board and a flight surgeon to represent the medical operations requirements to this board.

As onboard medical operations are multinational, they require sophisticated communication technologies for securely transferring medical data to and from the Station and among the International Partners' medical organisations. The medical office is heavily involved in defining and setting up such telemedicine capabilities for operational use, as well as in exploiting the feasibility of new medical hardware and procedures for onboard use and their potential for terrestrial applications.

All of the above activities lead to the ultimate and most challenging medical task: supporting the mission from a control centre. During a mission it has to be shown that the medical support programme was correctly applied, that the crew remains healthy and that the medical team responds appropriately to inflight anomalies. During the 18 missions so far with European astronaut participation, medical office personnel have provided support from NASA and Russian mission control centres in a consultant or 'second seat' capacity. The ISS medical support programme will significantly change the scope and responsibilities for the medical office and its staff.

The variety of tasks described above clearly shows that more than medical doctors are required for the medical support activities: biomedical engineers, information technology specialists, nurses and other medical support personnel.

Multilateral medical cooperation

Medical requirements and their implementation will be developed and agreed for formal input into the International Space Station Program (ISSP) office by a multilateral medical management structure. The MOUs between the International Partners establish these multilateral medical management groups; ESA is represented in all of these medical boards and panels.

The Multilateral Medical Policy Board (MMPB) is responsible for top-level medical policy and oversight, and reports to the ISS Program Office. The Multilateral Space Medicine Board (MSMB) is responsible for crew medical certification for mission increment training and flight. It also approves mission-assigned flight surgeons based on established standards, and reports on the medical certification status of astronauts to the Multilateral Crew Operations Panel (MCOP).

The Multilateral Medical Operations Panel (MMOP) develops common medical standards, certification criteria, medical care requirements, preventive medicine guidelines, operational countermeasures, medical hardware responsibilities, environmental monitoring requirements and operational procedures. In addition, it develops certification and training guidelines for ISS flight surgeons. The MMOP reports to the Space Station Control Board through the Mission Integration & Operations Control Board (MIOCB).

The MMOP may delegate issue resolution and requirements refinement to dedicated working groups in specific medical areas. ESA is highly involved in the Countermeasures, Radiation, Human Behaviour & Performance, Nutrition, EVA, Telemedicine & Communication, and Clinical Medicine & Standards working groups. The groups meet via video- and teleconferences and in person on an as-needed basis.

The MSMB and MMOP currently have two combined face-to-face meetings per year. The Spring meeting is usually held at JSC, while the Autumn meeting alternates among the Partner sites. Monthly video- or teleconferences are also held.

The Human Research Multilateral Review Board (HRMRB) has the fundamental responsibility of assuring the health, safety and wellbeing of human research subjects while ensuring ethical conduct of experiments. It reviews all proposed human research protocols after they have obtained proper approval by the Partner's appropriate review board (the ESA Medical Board in the Agency's case).

The charter of the HRMRB is approved by the Multilateral Control Board (MCB). However, the HRMRB is recognised as the ultimate decision-making authority within the scope of its responsibilities and thus is independent of the MCB or any other ISS management body.

After face-to-face meetings during the development phase of the board's charter, the HRMRB now meets via videoconferences about four times per year. Personal meetings are kept to a minimum. The board has so far reviewed and approved life sciences experiments up to and including Expedition 4.

The Medical Office provides the web and document server infrastructure for all four boards and all working groups, and is developing and maintaining all groups' web sites.

Mission operations

Providing an ESA astronaut in space with real-time support is the medical team's primary goal. In the past, the Crew Medical Support Office has supported all ESA astronauts on their missions aboard the Shuttle and Soyuz/Mir. However, the prime responsibility for the medical support was with either the NASA crew surgeon or the Russian medical control team. ESA physicians provided 'second seat' support. With the experience gained, the medical office is ready to enter the next phase of mission support – having an ESA crew surgeon assigned to ISS increments with full medical responsibility for the entire crew. This was made possible after negotiations within the MMOP and after finalising common medical training and certification standards for flight surgeons.

Figure 7. Flight surgeon on-console in MCC-H

The ISS medical support team considers a crew as a whole and will assign crew surgeons to the increment irrespective of crew composition. The crew surgeons will be assigned from a multinational pool of certified flight surgeons, usually around the time a crew is assigned to an increment. This crew surgeon will follow the crew through all training and mission preparation activities and will also provide the dedicated medical training to selected crew members to act as Crew Medical Officers in space.

During mission preparation and mission operations, a team of biomedical engineers will provide medical backroom engineering support within the control centre to support the ISS crew surgeon. It has been agreed that the prime medical responsibility will be in Mission Control Houston (MCC-H), and that the increment-responsible crew surgeon and support team will work 'on console' in MCC-H (Fig. 7).

As the crew surgeon assignment is independent of crew composition, it could happen that an ESA astronaut flies without an ESA flight surgeon in support. In such cases, it has been agreed that all Partners with crew members aboard may monitor the mission's progress and will be consulted on medical issues relating to their astronauts. This monitoring can take place in a second-seat role at MCC-H or it can be performed remotely from the Partner's control centre. The ESA medical office has adopted the latter approach. Real-time crew operations mission support will centre on the consoles and control rooms within EAC, where the interests of other centre entities are also consolidated.

Crew medical support preparation

Within the last 2 years, two flight surgeons have been certified as ISS flight surgeons by the MSMB. The third physician recently took up duties at JSC to begin training and to continue the medical support programme for the 10 ESA astronauts and their families resident in Houston.

Preparations for supporting Space Shuttle mission STS-100 are underway, specifically crew medical training, familiarisation with medical experiments and participation in simulations. ESA astronaut Umberto Guidoni is a crew member of this short-visit mission to the Station in April 2001.

The implementation of an Astronaut Fitness and Health Promotion plan at EAC, ESTEC and JSC has started.

The medical office will be ready to support ISS astronaut training activities at EAC by the end of 2002, and the real-time operations infrastructure at EAC will be ready about a year later to support the first tests and simulations.

Summary and outlook

EAC has developed over the last 10 years into the centre of expertise for manned space activities within ESA by contributing to a number of important cooperative missions. This role will be extended for ISS manned operations. Apart from its involvement with ESA astronauts and their onboard operations, EAC will have a key role in training all ISS astronauts on ESA elements and payloads. The medical support will ensure the wellbeing of European astronauts. Building up the medical capabilities and training preparations towards training-readiness in about 2 years is a challenging task.

Ten Years of the European Astronaut Centre (EAC)

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The European Astronaut Centre, the home base of ESA's Astronaut Corps, celebrated its 10th anniversary on 17 May 2000 with a media event highlighting the past, present and future of the Agency's manned space programme.

Introduction

The roots of ESA's European Astronaut Centre (EAC) reach back to 1977 when the Agency's first four astronauts were chosen, after a pre-selection process by the Member States, to train for the Spacelab-1 mission. After that highly successful multi-disciplinary international mission landed in December 1983, US President Ronald Reagan announced the Space Station project and invited the active participation of Europe, Japan and Canada. Europe simultaneously began its own ambitious programme, encompassing the Columbus Programme with the Attached Pressurised Module for the Space Station, the Manned-Tended Free Flyer, the serviceable Polar Platform and the manned Hermes space plane.

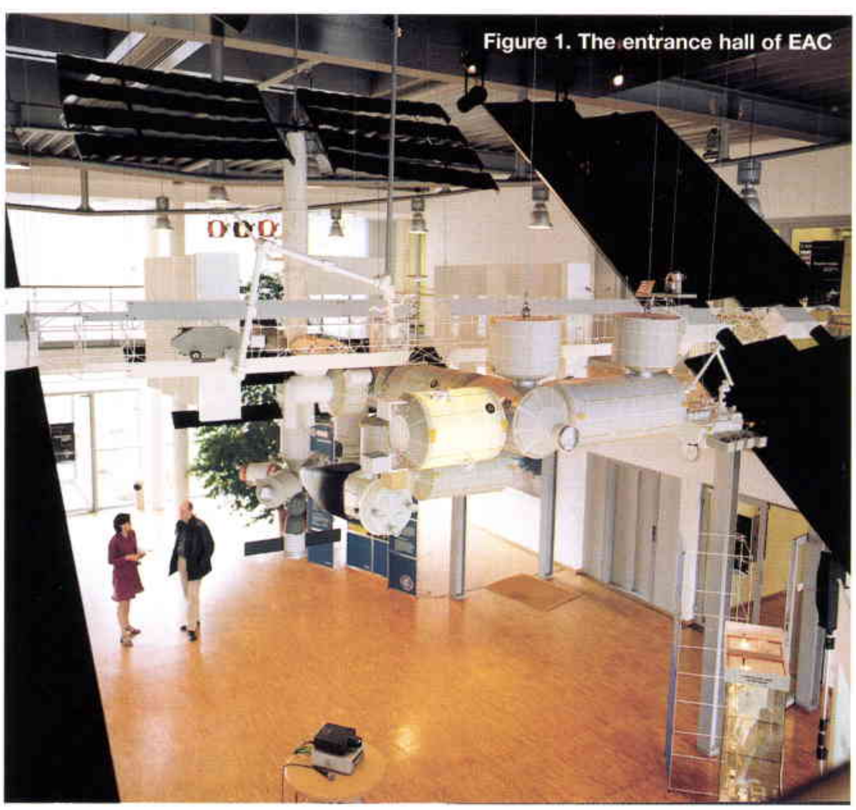


Figure 1. The entrance hall of EAC

In order to satisfy this long-term need for astronauts, ESA established EAC in Cologne (D). The Centre was formally created in May 1990, when the Host Agreement was signed between ESA and the German national authorities.

The European Astronaut Centre

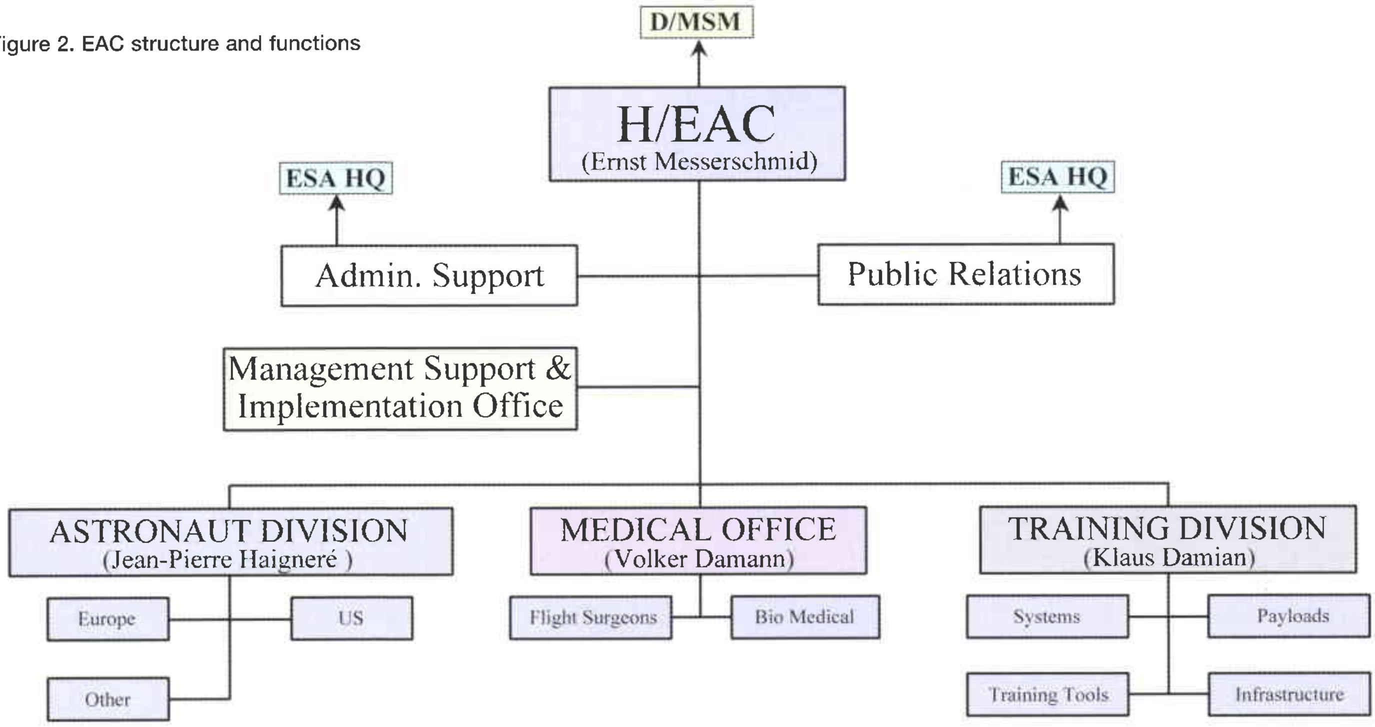
Following the selection of six astronaut candidates in 1992, EAC (Fig. 1) rapidly became the home base for all European astronauts. By then, Hermes, Free-Flyer and Polar Platform had been cancelled, and EAC focused on supporting ESA astronauts assigned to Space Station precursor missions aboard Shuttle/Spacelab and Mir. The training programme was developed in close cooperation with NASA and Russia's Gagarin Cosmonaut Training Centre and initially applied to the payload training for the Euromir-94/95 missions.

A key milestone was the Council Decision in March 1998 to integrate all European astronauts into a single European Astronaut Corps, started in 1998. This integration is now complete with the roster of 11 flown astronauts and five astronaut candidates and rookies. EAC's staff total will be almost 60 by the end of 2000 when the integration of national agency staff that began in March 2000 is completed. The German, French and Italian space agencies are contributing up to 30 seconded staff. The current organigram is shown in Fig. 2.

Astronaut Training Division

The Astronaut Training Division has contributed to a number of Columbus precursor missions and is now focusing on preparing Basic Training, Advanced Training and Increment-Specific Training for the International Space Station (ISS). Basic Training for ESA astronaut candidates is performed at EAC. Advanced Training and Increment Specific Training on ESA space elements (Columbus and the Automated Transfer Vehicle) and payloads will

Figure 2. EAC structure and functions



be provided at EAC to all ISS astronauts. Following training readiness at EAC, 2 years before the Columbus launch, about 70 ISS astronauts will be trained at EAC on average each year.

EAC's training facilities include a training hall, a Neutral Buoyancy Facility, physical fitness rooms, classrooms, communication and data handling facilities, computer-based training systems, trainer control rooms, workshops and refreshment areas. This infrastructure will be progressively outfitted with a Columbus Trainer, incorporating high-fidelity man-machine interfaces with simulated functionality, standalone training models for Biolab, Fluid Science Laboratory, European Physiology Modules, European Drawer Rack and European Stowage Rack, and a high-fidelity mechanical Columbus Mockup with Orbital Replacement Units for realistic maintenance training. ESA's Automated Transfer Vehicle (ATV) training facilities will also be hosted at EAC for crews to learn how to handle the pressurised cargo as well as ATV rendezvous and docking.

Crew Medical Office

The Medical Office provides a wide spectrum of crew support. It is responsible for medical issues during crew selections and astronauts' active careers, and provides the annual medical examinations for continuing flight certification. The infrastructure supports the astronauts and their families with, for example, nutritional advice, physical fitness regimes and human behavioural training for long-duration missions. During long-term missions aboard the ISS – lasting about 3 months – family teleconferencing and counselling will be provided.

EAC has three certified flight surgeons who represent the Agency on the various ISS medical boards. During on-orbit operations, the flight surgeons will have a valuable role in closely monitoring the astronauts' health during hazardous operations and when the crew is the subject of, for example, life sciences experiments. Based at the Mission Control Centres, they will act as ground-based ombudsmen for the crew with the scientists and payload operators. They are presently based in Cologne but when the Station is occupied they will spend extended periods in NASA's Johnson Space Center (JSC) and Russia's Star City as part of the consolidated ISS Crew Surgeon Team.

Astronaut Division

The Astronaut Division deals with all aspects directly related to ESA astronauts, such as:

- the definition and implementation of all processes, standards and criteria for the selection, recruitment, qualification and assignments. The division is the contact point for the Astronaut Offices of the other ISS partners and is, in particular, a member of the Multilateral Crew Operation Panel (MCOP), one of the high-level operational elements of the ISS organisation;
- the development of the ESA astronauts' operational capability, through the implementation of policies in the areas of professional and flight proficiencies as well as physical fitness;
- the career planning and the support to each astronaut during training, mission and post-flight activities;
- the organisation of the technical assignments of ESA astronauts in support of the Departments

of the Directorate of Manned Spaceflight and Microgravity;
- the safeguarding of crew safety.

The current assignment of each astronaut is shown in Table 1.

10th Anniversary Ceremony

During the preliminaries to the 10th Anniversary Ceremony on 17 May 2000, Antonio Rodotà, ESA's Director General, welcomed the invited guests and was particularly pleased to greet Dr. Lieb (Fig. 4), First State Secretary, representing the State of Nordrhein-Westfalen, and Minister President Clement, Mr Alain Benssoussan, the ESA Council Chairman, and Prof. Walter Kröll (Fig. 5), representing the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR). Other guests included Heads of Delegations of the ESA Council and of related ISS agencies, resident Science Attachés of ESA Member States and ISS International Partners, delegates of the ESA Programme Board for Manned Spaceflight, representatives of Astronaut Offices, German ministries and local authorities, and special guests involved in establishing EAC in Cologne.

In his address, Dr. Lieb referred back more than 10 years to when the State of Nordrhein-Westfalen and DLR took the risky decision to build a Crew Training Complex at the DLR premises on the outskirts of Cologne. This was long before it was certain that EAC would ever be established there. In today's parlance, the 'venture capital' was well invested. An important side effect is that it has proved to be an attraction for the younger generation, illustrating the importance of and the career possibilities offered by the natural and engineering sciences.

Figure 3. The EAC 10th Anniversary Ceremony

Table 1. ESA astronaut assignments and collateral duties

Jean-François Clervoy (F)	JSC: ISS display integration in Space Station Operations Branch
Claudie André-Deshays (F)	EAC: Microgravity Facilities for Columbus, supports medical operational and life science activities within D/MSM
Pedro Duque (E)	ESTEC: supporting the Module Project Division for Columbus
Reinhold Ewald (D)	EAC: supporting the training system build-up for ESA elements and payloads
Léopold Eyharts (F)	JSC: Mission Specialist training; collateral duties on Russian vehicles (Soyuz/Progress) and ISS Flight Crew Systems
Christer Fuglesang (S)	JSC: prime Support Astronaut for 2nd Station crew
Umberto Guidoni (I)	JSC: training for STS-100 Multi-Purpose Logistics Module flight (April 2001)
André Kuipers (NL)	ESTEC: Microgravity Payloads Division, coordinating scientific development inputs for MARES and ARMS
Paolo Nespoli (I)	JSC: Mission Specialist training; collateral duties in computer-based training, onboard training and system tests on ESA elements and payloads
Claude Nicollier (CH)	JSC: EVA Instructor in EVA Branch
Thomas Reiter (D)	EAC: supporting ERA and ATV projects
Hans Schlegel (D)	JSC: Mission Specialist training; collateral duties in mechanical, structural systems and crew equipment
Gerhard Thiele (D)	EAC: mission control capcom in JSC astronaut corps
Michel Tognini (F)	JSC: ISS Robotics Branch supporting MBS and ERA
Roberto Vittori (I)	JSC: Mission Specialist training; collateral duties in Shuttle system upgrades
Frank De Winne (B)	ESTEC: X-38/Crew Rescue Vehicle projects in human engineering and man-machine interfaces

ARMS: Advanced Respiratory Monitoring System. ERA: European Robotic Arm. EVA: Extra-Vehicular Activity. JSC: NASA Johnson Space Center. MARES: Muscle Atrophy Research.and Exercise System. MBS: Mobile Base System (for ISS robot arm) NASA Johnson Space Center.

Figure 4. Dr. Lieb, First State Secretary, represented the State of Nordrhein-Westfalen

Figure 5. Mr Alain Benssoussan (left) represented the ESA Council and Prof. Walter Kröll (second from left), represented DLR. With Prof. Kröll is Mr Jörg Feustel-Büechl, ESA Director of Manned Spaceflight and Microgravity, and (right) Mrs Strömberg, Chair of the Programme Board for Manned Spaceflight

One achievement of this memorable day was the very first gathering of the entire corps of ESA's 16 active astronauts at its home base. Over the years, the astronauts have been active in Europe, the USA and Russia.

Medialink Europe provided the following broadcast reports: 37 transmissions covered by Sky News, Deutsche Welle, Canal 24 Horas, TV5, TVEI, France 3, WDR3, ZDF, 3Sat, Bayern1, RAI News 24, RAI 3, ETB 2, Canal Natura TVE1, Antena 3, La2, CNN+ and Reuters. A total of 23 interviews were given by astronauts, plus five by other ESA representatives.

Astronauts and guests discussed the themes of 'European Astronaut Experience', 'Recent European Spaceflights' (see separate box) and the 'European Astronaut Identity' (Fig. 6).

European astronaut experience

As of August 2000, European national space agencies (D, F, I), ESA Member States (A, UK, B), and ESA had made 31 spaceflights with 27 astronauts since Sigmund Jähn's mission aboard Soyuz-31 in 1978. European astronauts have participated in 17 US Space Shuttle missions and in 14 Russian Soyuz missions to the Salyut-6, Salyut-7 and Mir space stations. Besides the development of an impressive scientific programme (space and microgravity sciences, technology), European astronauts have been involved at the highest skill level in space operations (EVAs, robotics) and have

Figure 6. Cornelia Czymoch (right) hosted the ceremony. Here, she is talking to Pedro Duque (left), Claudie André-Deshays (centre), Umberto Guidoni (second right) and Jean-Pierre Haigneré (right)

achieved the highest qualifications, such as Mir flight engineer and Soyuz escape vehicle commander. This European legacy and EAC heritage provides the basis for being part of the ISS community. Such an impressive background, including the development and operation of Spacelab, makes Europe a bridge between the ISS partners.

European astronaut identity
For more than 20 years, Europe has been involved in manned space programmes with a very specific approach arising from historical, cultural and geopolitical factors. Probably because basic science is a strong feature of the European culture, it has always been prominent in European space programmes, in comparison with the infrastructure developments of the USA and Russia. It is also reflected in the composition of the European Astronaut Corps, which has almost equal proportions of scientists and pilots.

Limited financial resources have driven Europeans to be imaginative, selective and creative – achieving more with less. In the space sector, the fact that Europe was following this avenue long before the era of 'cheaper and better' arrived was the key to survival. Looking for attractive cooperative ventures, we gained a unique two-sided expertise and became a powerful 'go-between'. These cooperative efforts form the basic framework of our present programme.

These factors have strongly influenced the European approach of organising a Single European Astronaut Corps, pooling the accumulated operational expertise of ESA's Member States. The 'European' identity of ESA's astronauts is not obvious because of the diversities of their multicultural backgrounds. However, ESA astronauts can often be easily identified when looking at groups of international astronauts working together in JSC or Star City. They are skilled at overcoming their differences and using them as a strength. They play a major role in all areas of space activities despite the dominant presence of the two major space powers. Our astronauts have a great ability to use foreign languages and to adapt to various situations, cultural differences and working standards.

However, no-one could develop capabilities aimed at pushing the frontiers of space without having a long-term perspective. This is why participation in the ISS not only focuses on providing Europe with clear visibility in the greatest space programme of the new century, but also on holding high the flag of all European citizens.

The future of EAC – the ISS and beyond
The future of EAC and its Astronaut Corps rests on three approaches:

Reliable service for International Partners
International crews bound for the ISS can expect to be trained on each partner's hardware. This means that up to four crews (with up to seven members each) will come to EAC annually for training on the Columbus laboratory, ATV, the ESA-provided payload facilities and data systems. This pace will be maintained over the planned ISS lifetime of 15 years. EAC's prime objectives include a good service, reliable infrastructure and friendly atmosphere to help the crews assimilate the information quickly. EAC is striving to become an equal partner with the training centres in JSC and Star City.

Using the ISS as a testbed for future activities
The multi-national, multi-facetted team of experts at EAC combines the experience of many spaceflights, and continues to improve the operational flow and support for the crews. Europe has yet to have an astronaut fly as a spacecraft commander, but the Member States' industrial capacity means that it could take the lead in developing and operating a manned space vehicle. This requires future-oriented crew preparation and planning – which EAC can now begin as part of its responsibility for the Single European Astronaut Corps.

Active promotion, preparation and participation in European manned space programmes beyond ISS
Many thousands of people visit European space centres every year, including EAC, and many more show their interest by attending presentations given by astronauts and space experts. This proves that the public is fascinated by space exploration – and such interest deserves to be taken seriously. EAC wants to be part of the next step in exploration – be it towards the Moon or Mars – with its astronauts, its experts and its support.

How to communicate our aims: the Space Learning Centre
The three approaches outlined above require careful development of EAC's staff skills and infrastructure. This will be supplemented by our outreach activities: the planned Cologne Space Learning Centre where the public can be involved in parallel with Europe's astronauts and their trainers. Educational training sessions will be located next to real ones, and virtual reality and other simulators will give visitors the chance to experience what it is like to set foot in space and live there. For many, that will be a dream come true.

Recent flights of European astronauts

STS-93: exploring the X-ray Universe

ESA astronaut Michel Tognini participated in the deployment of the Chandra X-ray observatory from the Space Shuttle's cargo bay. Chandra and ESA's XMM-Newton observatory, launched in December 1999 by Ariane-5, are exploring the violent hot surroundings of neutron stars, black holes and colliding galaxy cores. It was Tognini's second spaceflight, following his 1992 mission to Mir. The mission lasted 22-27 July 1999.

Figure 7. The STS-93 crew patch emphasises the deployment of Chandra. (NASA)

Figure 8. Michel Tognini in radio contact with Earth during STS-93. (NASA)

Figure 9. Chandra's deployment from the Space Shuttle payload bay into Earth orbit. (NASA)

Perseus: a Swan Song for Mir

On Mir's 13th birthday, 20 February 1999, ESA astronaut Jean-Pierre Haigneré lifted off for a record 189-day stay aboard the ageing spacecraft. Commander Afanasiev and flight engineers Avdeev and Haigneré completed their science research programme before putting Mir into hibernation as they left on 28 August 1999. The mission included a spacewalk that deployed a mast-mounted lightweight antenna. For the second time since Thomas Reiter in 1995, a European astronaut gained experience with the Russian Orlan spacesuit. On 11 August they saw the Moon's shadow sweeping across a cloud-covered Europe during the total eclipse.

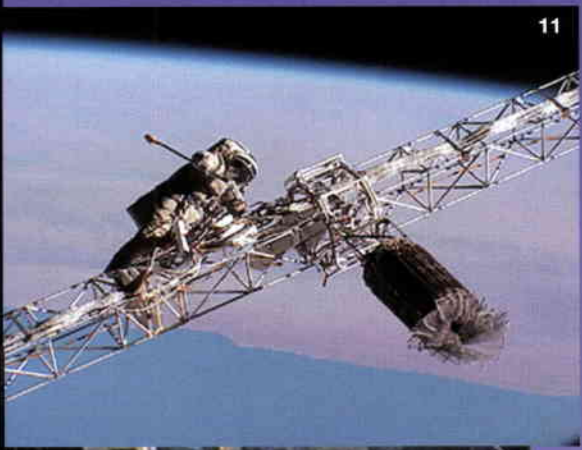


Figure 10. The Perseus crew was launched on 20 February 1999

Figure 11. Jean-Pierre Haigneré working on the antenna deployment during the 6-hour EVA in July 1999

Figure 12. Medical research with Cardiolab aboard Mir

Figure 13. Jean-Pierre Haigneré playing his saxophone during his leisure time aboard Mir

Recent flights of European astronauts

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STS-103: servicing the Hubble Space Telescope
Claude Nicollier and Jean-Francois Clervoy, ESA's most experienced astronauts, flew 19-27 December 1999 aboard the Space Shuttle to perform the third servicing mission of the Hubble Space Telescope. Hubble's guidance sensors had failed recently, leaving the observatory in safe mode. Clervoy used the Shuttle's remote manipulator to help his EVA crewmates, including Nicollier and UK-born Michael Foale, manoeuvre telephone-booth-sized hardware.


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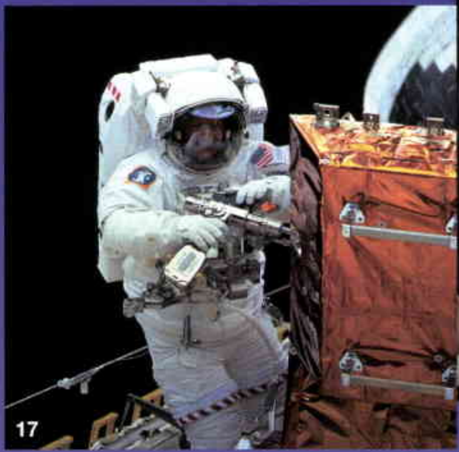
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Figure 14. The STS-103 crew patch. (NASA)

Figure 15. A spectacular liftoff for Shuttle *Discovery* shortly before Christmas 1999. (NASA)

Figure 16. Jean-Francois Clervoy with Claude Nicollier (left). (NASA)

Figure 17. Claude Nicollier opening a container of special tools for servicing Hubble. (NASA)

STS-99: an Earth Map in One Go
The Shuttle Radar Topography Mission (SRTM; 11-22 February 2000) and its crew of six, including ESA astronaut Gerhard Thiele, had the unique privilege of mapping most of the Earth's surface in a single flight. After processing the hundreds of data tapes from the two radars, Earth's inhabited surface will be known in 3D at unprecedented accuracy. For this, the Shuttle flight carried a receiving antenna on a boom protruding 60 m from the payload bay. Having lived one of his own, Thiele announced 'Keep your dreams alive!'


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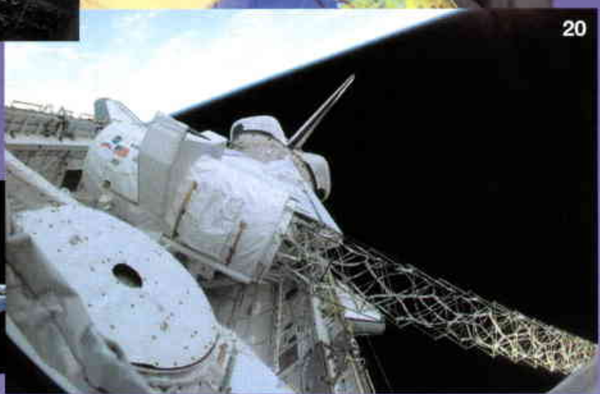
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Figure 18. Gerhard Thiele complementing the radar images with photographs. (NASA)

Figure 19. The radar measurement principle is demonstrated by Commander Kregel and Gerhard Thiele. (NASA)

Figure 20. Part of the impressive antenna mast structure extending 60 m from the Shuttle payload bay into space. (NASA)

Figure 21. SRTM image of the crater and outflow of Japan's Mount Oyama, which became active again this summer. (JPL)

New Concepts in Document Management for Space Projects

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The Integral Project based its documentation-management approach from the outset on electronic document sharing and archiving. Faster and wider availability of the most current information to all parties, rather than creating the 'paperless office', was the main objective. Implementation of the new approach required the capturing of documents in an appropriate electronic format at source, establishing new procedures for project-wide information sharing, and the deployment of a new generation of Web-based tools. Key success factors were the early adoption of Internet technologies and simple procedures for improved information flow.

Introduction

Managing complex scientific projects like ESA's Integral mission (to be launched in April 2002) requires a high degree of collaboration with numerous mission participants. ESA's major external project partners are the industrial consortium, contracted to develop the spacecraft, the instrument teams, the spacecraft and science operations centres, and the launch authorities. The project also involves in-house expertise for such activities as mission planning and operations, and spacecraft testing. During the development phase, the ESA project team plays the pivotal role in directing the information flow and the decision-making process across the project organisation (Fig. 2).

It is acknowledged that effective information sharing among all project participants is a critical success factor for completing the project on time and within budget. However, the wealth of technical and managerial information has traditionally been stored and distributed in tens of thousands of documents. (Table 1). While documents have been

Figure 1. The Integral Structural Thermal Model being readied for testing in the Large Space Simulator (LSS) at ESTEC in Noordwijk (NL)

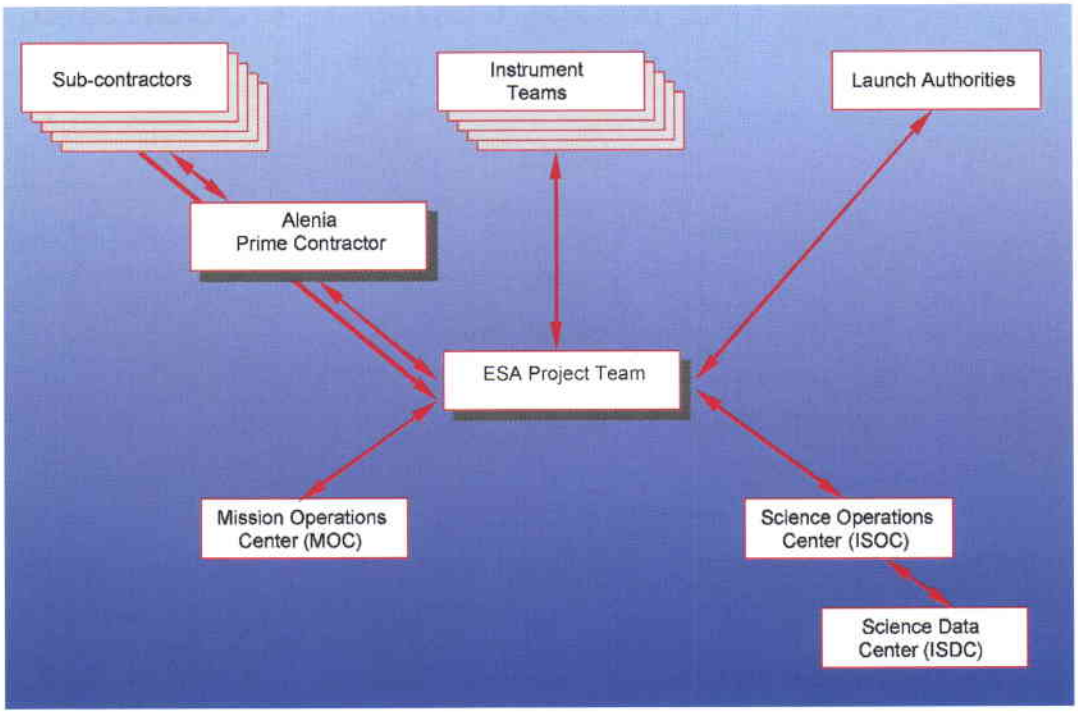


Figure 2. Main documentation flows. The main participants in Integral are the prime contractor (Alenia) and the industrial consortium of about 30 companies, the instrument teams, the Mission Operations Centre (MOC) at ESOC, the Integral Science Operations Centre (ISOC) at ESTEC and the Integral Science Data Centre (ISDC) in Geneva. The Proton launcher is being provided by Rosaviakosmos

Table 1. Scaling the problem

Project	Number of documents over project lifetime
Integral*	36 000
XMM	64 000
Cluster-I/II	51 000
SOHO	41 000
ISO	79 000

*Two more years to go

produced with computers for a considerable time, incompatible, constantly changing technologies have limited progress in document management. Paper has been the preferred medium for storage, with facsimile and mail being the main distribution services. Paper documents are still best for reading and red lining, but their content is not easily accessible and sharable with a geographically dispersed team.

Focused on efficiency improvements, the ESA Integral project team saw in emerging Internet technologies an opportunity to ensure the timely availability and easy access to the most current documents for all project participants, whilst at the same time reducing the effort involved in document management. By taking a broad view, the Integral project considers documents to include any kind of information, ranging from technical specifications, reports and design drawings, to correspondence and minutes of meetings. A system for electronic document distribution and archiving was devised and implemented in cooperation with the industrial Prime Contractor, Alenia Spazio, in 1995, at the beginning of the project definition phase.

Choosing a system-independent document exchange standard

In a large project environment, documents are produced with a variety of tools and platforms, ranging from simple word processors to complex engineering design systems. In such a heterogeneous environment, and one that is subject to frequent information-technology changes, electronic document sharing can be unreliable and costly. Even though some proprietary document formats are in principle cross-platform compatible, documents may still appear very different when viewed or printed on different equipment. Different implementations of document styles or variations in the rendering of graphics are typical elements impacting the visual integrity of electronic documents. Considering the project's mixed technical — scientific — commercial environment, with many diverging needs and specific constraints, it was clear that a comprehensive 'one-size-fits-all' document preparation tool was not available on the market.

A key decision for Integral in implementing electronic document distribution and archiving was to use a system-independent document exchange standard. While technical capabilities played a significant role in the analysis, company policies and cultures had to be taken into account as well.

Two options were considered at that time (1995):

– Use of the Standard Generalised Markup Language (SGML)
The most promising hardware- and software-independent standard at that time was SGML. Although the prime contractor Alenia had already gained SGML experience within the International Space Station programme, the complexity of implementing the concept across all participants was beyond the scope of the Integral project.

– Use of the Portable Document Format (PDF)
While the life span of such a proprietary format was not assured, this option was retained because of its simplicity and cost-effectiveness. At the end of the document-preparation process, it is converted into a PDF file, readable across a wide range of platforms whilst still preserving its original appearance. The minimal investment and the compatibility with the installed document-preparation tools made this a cost-effective solution, attractive to all project partners.

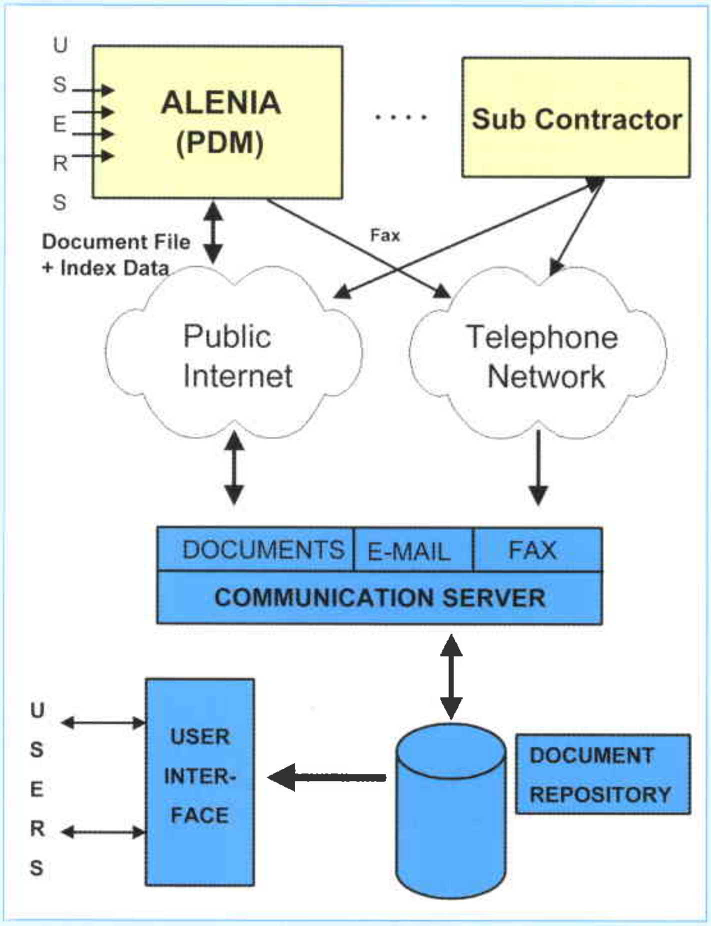
Setting up distribution and archiving tools
In the light of the different needs for automating engineering and management processes, ESA and Alenia implemented different – though complementary – systems. Beyond the standard features present in both systems, like providing controlled document access (both internal and external), the ESA system focuses on project-wide document distribution and archiving (see accompanying panel 'The ESA Science DMS'). The Alenia system offers additional functions to control the engineering information. By relating all the data to the product structure, the system allows detailed configuration management down to each configuration item of the spacecraft (see panel 'The Alenia Integral PDM').

Simple procedures
Based on the above tools, procedures have been devised within the project to register, distribute and archive the documentation effectively. The main flow of information is between the spacecraft industrial team and the ESA project team. Typically, a subcontractor issues a document in PDF format to Alenia, with a working copy to ESA. The Prime Contractor registers the document and forwards it with the appropriate index information. When it reaches the ESA communications server, the document and its index are automatically pre-registered. After verification, the document registration is confirmed and the distribution process can be performed electronically both within the ESA team and to outside participants. In addition to this main link between industry and the Agency, the other flows of information between the project and the other participants are handled in a similar manner. Where the source documentation is not available electronically, the paper document is incorporated into the system through scanning, either at Alenia or at ESA.

The system is effective in that:
- It affords the ESA and Alenia project teams immediate access to the entire project documentation, ranging from formal technical documents to the latest correspondence, faxes and e-mails. The Alenia staff also have detailed product configuration information readily available.
- Support staff within ESA and Alenia with appropriate access privileges can also remotely consult the entire archive, which is particularly helpful, for example, for operations based in ESOC, for test campaigns at ESTEC, or for launch-related matters involving ESA's Moscow Office and in the future the Proton launch site.

The ESA Science DMS

The ESA Science Document Management System (DMS) enables electronic distribution and archiving. Documents transferred via the public Internet to the ESA communication server are automatically moved to the document repository, registered and distributed to the final recipients. Likewise, faxes are automatically converted to PDF format, archived and distributed. An Internet search-engine-like interface provides easy access for authorised users.

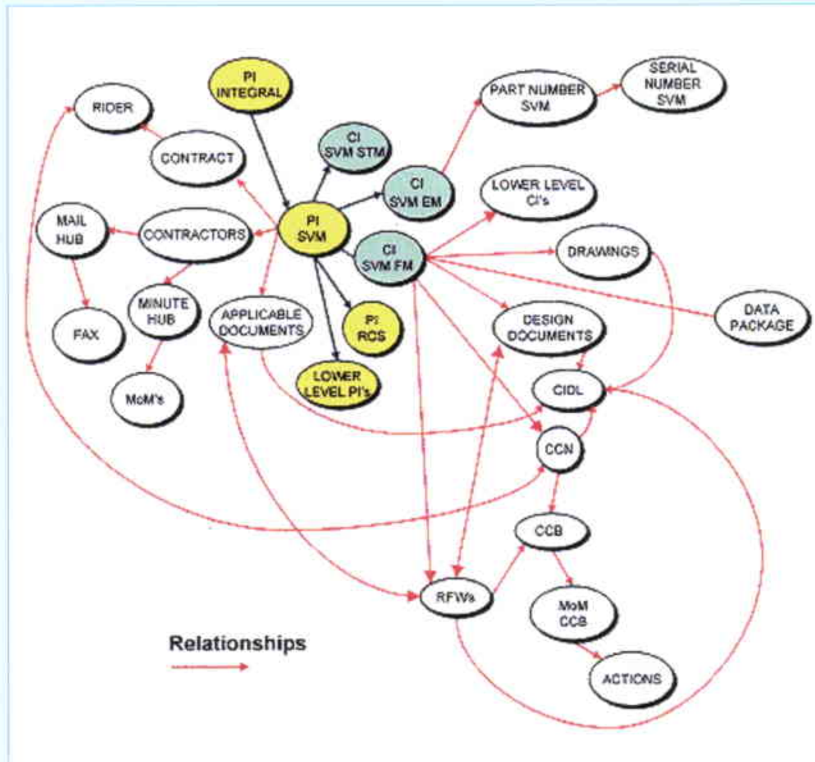


The Alenia Integral PDM

The core of the Alenia Product Data Management System (PDM) is the product tree, a hierarchical structure breaking down the spacecraft into all of its lower-level elements. Each relevant element in the product tree can be associated with all of its documentation, which includes engineering, configuration and management information, such as design data, drawings, contract changes, applicable specifications, technical assessments and minutes of meetings.

Based on this key data set, the system can monitor:

- *the evolution of the baseline product information*
- *the planning and release of new product information, such as specification updates*
- *multiple spacecraft configurations, such as the various development models or specific test configurations*
- *critical spacecraft properties and technical capabilities, such as mass or power-consumption budgets.*



- Paper copies are still circulated, in particular for reference documents requiring detailed scrutiny. However, transfer times have been reduced significantly and a document can be issued and distributed to all participants under full configuration control within a few hours.

The initial implementation challenge was coping with the wide range of platforms and the large number of minor adjustments necessary to individual set-ups. These system issues could appear in any of the many components and links between the user's desktop and the document repository. More stable configurations and wider experience and acceptance of web-based tools has largely helped to overcome this. More procedural aspects have been the allocation of individual user access rights to the system, and definition of appropriate distribution lists. This issue is much more evident in the electronic environment than in the paper one, because of the wider awareness of the available documentation among the users.

Outlook

Based on such an infrastructure, information flows between the project participants can be further enhanced. An application that has been successfully implemented provides support to project reviews for both ESA and industry. Using the electronic documentation system, a data package can be posted on the web for consultation by the review team. Comments or discrepancies identified by that review team can then be registered and tracked until all issues are closed. Similar extensions have been deployed in support of document-intensive product-assurance activities, although not yet fully implemented in the Integral project. The Nonconformance Control application, for example, allows the systematic recording, reporting and tracking of nonconforming items and of the associated corrective actions.

Conclusion

A key transition was made in the Integral project by basing the documentation management on electronic document sharing and archiving, covering the main aspects of a document's life, from creation to distribution. The approach has been particularly well received by Alenia and its industrial team. Based on this positive experience, documentation is being managed in a similar way for all new ESA science projects. With some variations, the concept and the ESA Science DMS are also being used successfully for other major ESA missions, such as the Metop project.

Programmes under Development and Operations

(status end-September 2000)

In Orbit

	PROJECT	COMMENTS
SCIENCE PROGRAMME	SPACE TELESCOPE	LAUNCHED APRIL 1990
	ULYSSES	LAUNCHED OCTOBER 1990
	SOHO	LAUNCHED DECEMBER 1995
	HUYGENS	LAUNCHED OCTOBER 1997
	XMM-NEWTON	LAUNCHED DECEMBER 1999
	CLUSTER-II	RE-LAUNCHED MID 2000
APPLICATIONS PROGRAMME	MARECS-B2	POSSIBLE NEW LEASE
	METEOSAT-5 (MOP-2)	OPERATED BY EUMETSAT
	METEOSAT-6 (MOP-3)	OPERATED BY EUMETSAT
	METEOSAT-7 (MTP)	OPERATED BY EUMETSAT
	ERS - 1	MISSION ENDED MARCH 2000
	ERS - 2	LAUNCHED APRIL 1995
	ECS - 4	OPERATED FOR EUTELSAT
	ECS - 5	MISSION ENDED MAY 2000

Under Development

	PROJECT	COMMENTS
SCIENTIFIC PROGRAMME	INTEGRAL	LAUNCH APRIL 2002
	ROSETTA	LAUNCH JANUARY 2003
	MARS EXPRESS	LAUNCH JUNE 2003
	SMART-1	LAUNCH LATE 2002
	FIRST/PLANCK	LAUNCH FEBRUARY 2007
COMMS / NAV. PROG.	ARTEMIS	LAUNCH DATE TBC
	GNSS-1/EGNOS	INITIAL OPS. END 2003
	GALILEOSAT	FIRST LAUNCH 2003
EARTH OBSERV. PROGRAMME	EOPP	
	EOEP	INCL. CRYOSAT, SMOS, GOCE
	ENVISAT 1/ POLAR PLATFORM	LAUNCH JUNE 2001
	METOP-1	LAUNCH UNDER REVIEW
	MSG-1	LAUNCH JANUARY 2002
MANNED SPACE & MICROGRAVITY PROGRAMME	COLUMBUS	LAUNCH OCTOBER 2004
	ATV	LAUNCH APRIL 2004
	X-38	V201 TEST FLIGHT JULY 2002
	CRV	OPERATIONAL 2005
	NODE-2 & -3	LAUNCHES NOVEMBER 2003 & JULY 2005
	CUPOLA	LAUNCH JANUARY 2005
	ERA	LAUNCH OCTOBER 2002
	DMS (R)	LAUNCHED JULY 2000
	MELFI	LAUNCH OCTOBER 2001
	GLOVEBOX	LAUNCH OCTOBER 2001
	HEXAPOD	LAUNCH SEPTEMBER 2004
	EMIR	
	MFC	BIO, FSL, EPM in COLUMBUS
LAUNCHER PROGRAMME	ARIANE-5 GENERIC	V504 LAUNCHED DECEMBER 1999
	ARIANE-5 EVOLUTION	FIRST LAUNCH FEBRUARY 2002
	ARIANE-5 PLUS	
	VEGA PHASE 1	
	FESTIP	REUSABLE LAUNCHER DEFIN.
	FTLP	TECHNOLOGY DEVELOPMENT

DEFINITION PHASE
OPERATIONS
MAIN DEVELOPMENT PHASE
ADDITIONAL LIFE POSSIBLE
LAUNCH/READY FOR LAUNCH
RETRIEVAL
STORAGE

XMM-Newton

The XMM-Newton observatory has entered its routine observation phase, and the emphasis in the observing programme is gradually shifting towards executing observing proposals selected from an open invitation to the astronomical community, which was issued in January 1999.

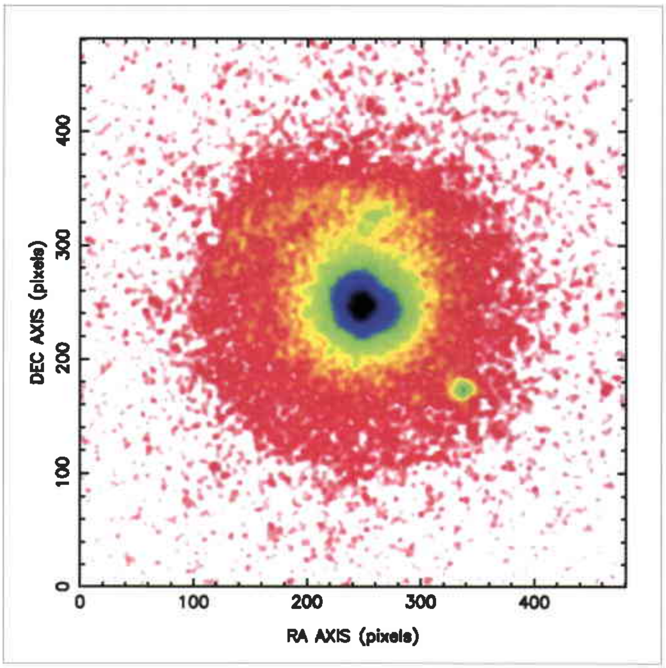
The observatory is working according to expectations, and the most notable events were the two major solar flares that took place during the summer. The change in instrument performance as a direct effect of these solar flares was also as expected from the pre-launch predictions, and constitutes a minor change in instrument performance.

The most important change in the observatory has been the failure of two CCDs in the Reflection Grating Spectrometer (RGS) cameras, in January and in September. As the RGS instrument consists of two identical cameras each containing 9 CCDs, and as the two failing CCDs do not cover the same spectral range, the full scientific performance can still be achieved, albeit at the cost of some observing time. Following an operating-efficiency review, a number of changes and upgrades to the ground segment were agreed and implemented, which will result in more efficient use of the observing time available.

After the execution of all observations constituting the so-called XMM-Newton performance-verification phase, a large team of scientists from all over Europe, and from the USA, have submitted more than 50 high-quality scientific articles for a special issue of the magazine 'Astronomy and Astrophysics' in January 2001. Regular updates on the most striking results obtained by the XMM-Newton observatory can be found at:

http://sci.esa.int/xmm.

EPIC MOS image of supernova remnant G21.5-09



Cluster

After the two very successful launches on 16 July and 9 August, all four Cluster spacecraft have been performing in an excellent manner. All system units have been tested and commissioned and exhibit nominal performance. The four spacecraft have undergone two long eclipses (3 h 8 min to 3 h 42 min) and a short one (1 h 11 min to 1 h 23 min), exhibiting very good thermal and power characteristics.

Commissioning of the scientific payload started on 22 August and is ongoing. Commissioning activities have been successfully completed on spacecraft 2 (Salsa) by ASPOC, on spacecraft 3 (Samba) and 4 (Tango) by CIS, Peace and Rapid. FGM has completed all activities on all four spacecraft. The remaining experiments are completing commissioning on spacecraft 1 (Rumba) and 2 (Salsa). The four wire booms have been successfully deployed to a total length of 88 m on two spacecraft.

All commissioning activities are currently planned to be completed by 23 December.

Rosetta

The Electrical Qualification Model (EQM) programme is now progressing at Alenia in Turin (I). All of the payload units have been delivered and integrated onto the Payload Support Module (PSM). The power and data handling equipment is functioning satisfactorily on the Bus Support Module (BSM), together with some Attitude and Orbit Control System (AOCS) units. The PSM and BSM have been successfully assembled together and their integrated testing has just started. Various teething problems have been encountered which have necessitated double-shift working to ensure completion of the EQM programme before starting work on the flight model in March 2001. Some equipment items (transponder, star tracker and software) have encountered

Rosetta

problems during development and contingency plans have had to be put in place for their late delivery.

Most of the attention regarding the payload has been directed towards the EQM. However, the Experiment Final Design Reviews (EFDRs) are now taking place, lasting until November, in order to provide inputs for the mission's Critical Design Review (CDR).

The EQM Lander has completed its integration, and an end-to-end interface and data flow test has been successfully performed. It has been delivered to Alenia and the Lander elements that are mounted on the Orbiter have been successfully integrated. The development of the landing gear and some experiments for the flight model are running behind schedule and are being given maximum attention in order to ensure timely delivery.

The interface control document for the Ariane-5 launch vehicle has been finalised, and the final contract is expected to be signed before the end of the year.

The development of the ground system is progressing satisfactorily. The site activities for the construction of the new 35 m antenna in New Norcia (Aus.) are going according to plan. The Ground Segment Design Review was held successfully in September, with no 'show stoppers' being identified.

Integral

The spacecraft, payload, launcher and ground-segment activities are progressing as planned. A payload review in early October concluded that the four scientific instruments for Integral have overcome their development problems, and the planned April 2002 launch was confirmed.

The spacecraft Service Module flight model is now practically complete. The integration of the flight models of the scientific instruments with the Payload Module is due to take place at Alenia Spazio's facilities in Turin between October 2000 and May 2001.The spacecraft environmental test campaign at ESTEC will follow immediately thereafter, in the second half of 2001.

Preparations for the third part of the System Validation Test (SVT C) are in progress. The test is to be completed in December 2000. The scope of SVT C covers the verification of spacecraft contingency recovery and instrument flight operations procedures.

The scientific community has shown great interest in the Integral project by submitting a large number of observing proposals and by actively participating in the 4th Integral Workshop, held in Alicante (E) in September.

Earth Observation Envelope Programme (EOEP)

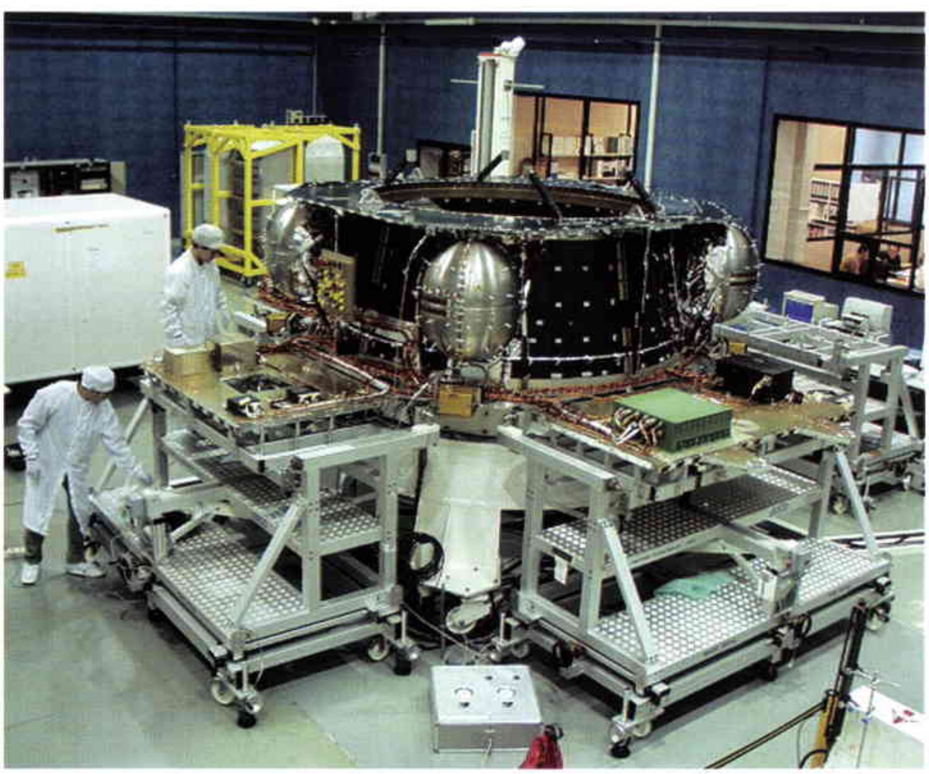
After the review of the Phase-A results, the Cryosat Phase-B was started in August.

For the GOCE mission, the proposal received in July 2000 for Phase-B/C/D/E1 has been evaluated and a contract proposal will be submitted to the October meeting of ESA's Industrial Policy Committee (IPC). In addition, it has been agreed to include Level-2 data processing within the scope of the GOCE project activities. This activity will be performed by the European GOCE Gravity Consortium (EGG-C), with the participation of the main scientific institutes involved in the GOCE project.

The SMOS Extended Phase-A was kicked-off in September. Activities on mission-performance simulation are about to start. Preparations are starting for a salinity data-processing study for SMOS.

The activities related to the ADM/Aeolus instrument pre-development design are progressing nominally, with a view to design selection and implementation next year.

The Integral Service Module flight model in the Alenia Spazio clean room, in Turin (I)



The analysis of the large number of proposals (81) received as a result of the 'Call for Ideas for Market Development' resulted in the identification of 26 'short-term' initiatives to be started as a priority. Six of these activities have already been kicked-off in September. An Invitation to Tender (ITT) for 'long-term' market-development activities has been generated.

Earth Observation Preparatory Programme (EOPP)

Ten proposals have been received in response to the 'Call for Mission Ideas' for the second cycle of Earth Explorer Core Missions. Their evaluation has been started and will be finalised by the Earth Science Advisory Committee in October, with the recommendation of a shortlist of candidates for further assessment. The Director of Applications will propose the implementation plan for these recommendations to the Earth Observation Programme Board (PB-EO).

The preparations for Earth Watch have continued, with a number of supporting studies being undertaken.

Meteosat Second Generation (MSG)

The MSG-1 Spacecraft underwent its Flight Acceptance Review (FAR) in August 2000 as planned. Final tests will be executed in order to ready it for the Pre-Storage Review (PSR) planned for the end of this year. Removal from storage is presently planned for mid-2001, in line with an anticipated launch in January 2002 on an Ariane-4 using a dual-launch configuration.

A shock-test programme is being elaborated to qualify MSG-2 and 3 (and potential follow-on models MSG-4 and 5/6) for the shock environment experienced during an Ariane-5 launch.

MetOp

The arrival of the combined Search & Rescue and Data Collection subsystem at the Payload Module (PLM) AIT site and its subsequent integration in the PLM engineering model represents another important achievement in the MetOp Assembly, Integration and Test (AIT) programme. This step completes the electrical/mechanical and functional interface verification of a first group of instruments providing services similar to an instrument package presently operated by NOAA within the Tiros satellite programme. The engineering-model results provide confidence that MetOp's avionics have the correct interface for the accommodation of this instrument group.

Payload Module integration of the second group covering new-generation European instruments is now imminent and will start with pre-integration of the engineering model of the improved Global Ozone Monitoring Experiment (GOME-2).

The qualification of the satellite structure is running in parallel. The structural-model AIT programme at Service Module and Payload Module level is nearing completion with the evaluation of their respective static load tests. The shipment of the models to ESTEC is anticipated towards the end of this year, leading up to a satellite-level test campaign covering acoustic and vibration tests now planned for early in the second quarter of 2001. This test campaign will be adapted to cover the satellite's compatibility with both the Soyuz-ST and Ariane-5 launcher environments.

Work continues in the meantime to catalogue all launcher-induced changes for the MetOp satellite programme, and iterations with the launcher authority have intensified from September onwards.

September also marked the start of MetOp flight-model activities at the PLM AIV site, having confirmed the test readiness of the PLM for flight-avionics integration. The alignment of the overall schedule and integration logic of this first flight model with the customer-furnished-instrument delivery dates continues.

The Alcatel/ESA/Eumetsat Project Managers during the Flight Acceptance Review at ESTEC in August 2000, with the MSG-1 model on the right and the smaller model of the first Meteosat generation on the left

Envisat

System

The system activities have been focusing on:

- performing the Ground Segment Overall Verification (GSOV) tests to verify interface compatibility between the satellite and the ground segment (PDS and FOS) as well as the mission-planning interfaces between the FOS and PDS
- progressing the in-orbit switch-on phase definition
- progressing preparation of the commissioning phase, with the payload calibration and validation teams, and defining a data-circulation test campaign to be performed in October 2000
- starting preparation of the Flight Acceptance Review, data-package definition and activation of mini-teams for the different disciplines to prepare the documentation for this review.

Satellite and payload

Major progress has been achieved this summer in the flight-model satellite verification programme, with two major environmental tests, the acoustic and the sine-vibration tests, being successfully concluded. These two tests have verified the compatibility of the flight-model satellite with the flight loads induced by the Ariane-5 launcher.

The acoustic environmental test was performed in the LEAF (Large European Test Facility) at ESTEC with the complete flight-model satellite in its launch configuration. Prior to this test, the solar array was integrated on the satellite and a test, including release of the solar-array pack and partial deployment of the arm, was performed under the control of the satellite Service Module software.

The satellite was then installed on the ESTEC HYDRA facility for the sine vibration tests. HYDRA is a new three-axis large shaker and Envisat was the first satellite to use this facility. Thanks to the timely availability and extremely good behaviour of the shaker, the test was carried out for all three axes without interruption and was satisfactorily concluded at the end of August, ahead of schedule. Following this test, Arianespace has confirmed that Envisat has been exposed and qualified to loads well above the expected launch-phase environment.

The Envisat flight-model satellite installed on the HYDRA test facility at ESTEC (NL)

The post-mechanical-test verifications are now in progress to ensure that all deployment mechanisms and all satellite functions are still operating nominally. During this phase, the second Solid State Recorder will be integrated onboard, the ASAR antenna will be deployed, and phase-2 of the satellite functional tests will be completed. The new release of the Payload Module Computer (PMC) software required for these tests is currently under validation. Several validation platforms have been activated in parallel to speed up this effort and to minimise its potential negative impact on the schedule. The satellite tests will include execution of a realistic payload operation scenario commanded and monitored from the Flight Operation Control Centre (FOCC) at ESOC in Darmstadt (D). This phase will also include retrofitting of the ASAR antenna to install the six tiles that are still missing and to obtain a complete operating 20-tile antenna for the coming Radio Frequency Compatibility (RFC) test.

Before the end of the year, the last major test will be initiated: it will consist of verifying the electromagnetic and radio-frequency auto-compatibility between all payload instruments and service subsystems. For this test, the complete flight-model satellite, with antennas deployed, will be operated nominally, with radars (ASAR and RA-2) radiating, telemetry/ telecommand links operating, and radiometer/spectrometer instruments in their operational receiving modes.

The AIT programme has progressed well over the last quarter and the coming tests, in particular with the PMC software, merit special attention in order to maintain the target launch date of end-June 2001.

Ground segment

The FOS element is nominally on schedule. Flight Operation Procedures

(FOP) are in production and a joint ESA-Industry working group has being formed to go into the details of the LEOP recovery procedures. Use of the Svalbard (N) station is in preparation, nominally for S-band telemetry/telecommanding (TM/TC) for the Kiruna-blind orbits, but also with an X-band option as a backup for the data dumps nominally foreseen via Artemis.

Upgrading of the PDS to version V3 is currently in progress. This upgrade includes some updating of the processing algorithms to install the last updates from the Expert Support Laboratories. It reflects all data format changes registered while integrating the flight-model instruments on board the satellite, as well as integrating up to date and more powerful computers. Installation of PDS V3 version is already in progress at ESRIN for the Payload Data Handling Station.

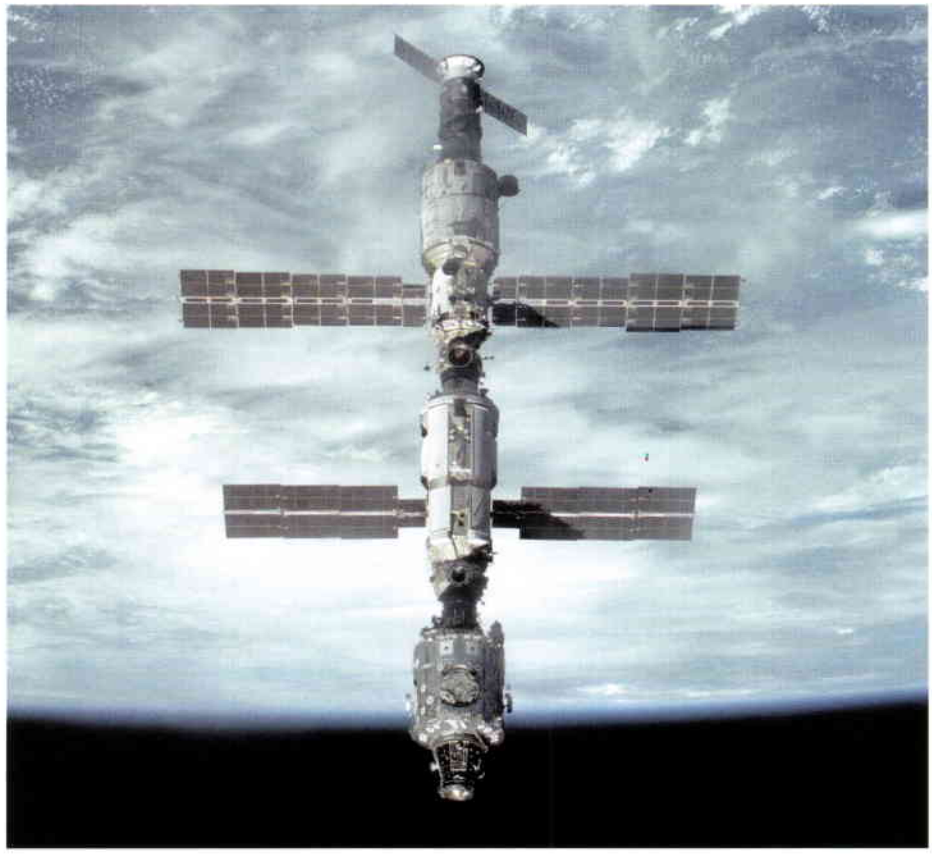
The groups that will support the in-orbit Calibration and Validation activities have been established and commissioning-phase preparation activities are in progress. A rehearsal data-circulation campaign is planned in October, with all Principal Investigators (PIs) involved in validation campaigns; the participants will also have access to the Envisat User Service Facilities.

To prepare the users for the exploitation of the Envisat data products, which will be delivered by the PDS in near-real-time and offline, a suite of simulated PDS products is being released on CD-ROM. These CDs are supported by ENVIVIEW software, which provides an online description as well as a data-product handling capability. They will be distributed to all of the scientists participating in the ERS-Envisat Symposium in Gothenburg (S) in mid-October, as well as being made available on request from the Envisat Help Desk: eohelp@esrin.esa.it.

International Space Station

ISS Overall Assembly Sequence

Following the Service Module's launch on 12 July and the successful docking with Zarya/Unity on 26 July, the ESA-provided DMS-R continues to provide guidance, navigation and control of ISS. Two further missions to the ISS have been completed since then, a Russian re-supply mission in August and an American logistics mission in September. Revision-F of the ISS Assembly Sequence was approved in August, confirming a Columbus launch date of October 2004 and including the first ATV mission in April 2004.



Photograph of the ISS, taken by the STS-106 crew. From top to bottom: the Russian 'Progress' re-supply ship, the Russian Service Module 'Zvezda', the Russian FGB 'Zarya', and the US Node 'Unity'

Preparations for the next logistics flight to the ISS in the first half of October (Flt.3A) continued on schedule, clearing the way for the first Expedition Crew launch at the end of October. Informal inputs from RSC-Energia indicate that if funding for the Russian Science Power Platform (SPP) becomes available in early 2001, which is not certain, the earliest launch date for the SPP would be in 2004.

Columbus Laboratory

The delay to the integration schedule of the flight unit related to the quality problems associated with fibre-optic cables has been minimised, as sufficient quantity of the available cable has passed revised acceptance tests. The Flight Unit acceptance Modal Survey Test is underway, and offline mechanical integration has been initiated. Testing on the Electrical Test Model is proceeding, with all manually commanded functions having been completed. The PICA Critical Design Review (CDR) has been completed, and the System CDR/Safety Review-II cycle has been initiated.

Progress on the Rack Level Test Facility and the Crew Trainers is in accordance with the required schedule.

Columbus Launch Barter

Nodes-2 and -3

The schedule for the Node-2 delivery is in jeopardy due to contractual problems between the prime and the secondary structure subcontractor. ASI, which (at the request of NASA) has been delegated by ESA to manage the project, has requested help from ESA to resolve this problem. The Structural Test Article manufacturing is complete and it has been mounted in the test facility ready for the pressure/inertia loads test campaign. The flight-unit Node-2 structure has been finished and is being integrated for the modal-survey test. The Node-2 CDR is planned for early next year, assuming that the above contractual problem is resolved.

Cryogenic Freezer Racks

The deadline for Phase-B/C/D proposal submission by Industry has been extended to December 2000.

Crew Refrigerator / Freezer
Phase-B0 has been completed and will be followed by a Phase-B/C0, which should start at the end of November.

Cupola
The machining of the dome and ring for the qualification model has been finished, and the sub-elements were delivered to the Prime Contractor this summer, ready for welding. Problems that related to the change from one-crew to two-crew EVAs have been satisfactorily resolved. Manufacturing of the equipment for the Qualification Model (QM) is well advanced; the (NASA-provided) window glass has been delivered and inspected, and integration into the window frames will soon begin. Problems with the Shutters subcontractor have been resolved and the Shutters also are in QM manufacturing. Preparations for the Neutral Buoyancy Testing early next year are underway.

Automated Transfer Vehicle (ATV)
A top-level Industrial committee has been formed to recommend the necessary recovery activities for the project, following the initial assessment of the Preliminary Design Review (PDR) results. Their managerial and technical recom-mendations are under consideration for implementation. Resolution of the key issues resulting from the PDR is in work with the Prime Contractor, RASA and NASA. In particular, solutions to the power/thermal and guidance/navigation/ rendezvous problems are converging. The final review board is expected to be held before the end of the year.

Following the decision to launch ATV on the Ariane-5 Plus configuration, an evaluation of the impacts of the launch environment on the standard Russian flight hardware is being performed. The manufacturing and welding of the primary structure of the Dynamic Test Model has been completed.

X-38/CRV and Applied Re-entry Technology (ART)
Further X-38 deliveries and activities continue, and integration of the orbital flight test vehicle (V201) is underway at Johnson Space Center (JSC). The flight has been delayed until July 2002, as a result of revision of the Shuttle manifest. The next series of Drop Tests, this time of the updated aerodynamic shape corresponding to that of the operational CRV, and with European parafoil guidance and control software on board, will take place in the fourth quarter of this year.

The additional Declaration for the ESA participation in the operational CRV was approved by the 35th Manned Space Programme Board, and the corresponding Phase-1 RFQ was subsequently released. Further negotiations with NASA have taken place, with good progress, with respect to the potential Barter. Selected early tasks of ESA CRV activities in the areas of aero-/thermodynamics, avionic analyses and Man Machine Interface (MMI) display requirements and developments are underway and proceeding nominally.

Ground-segment development and operations preparation
Work continued on agreeing the approach to, and documentation of, the Columbus Control Centre facility-level design and development. The next major milestone is the Columbus-CC System Requirements Review (SRR), which is planned for January/February 2001.

Near-term activities concerning ATV Control Centre design and development definition have been discussed with CNES during the first Progress Meeting of the Phase-B2 extension contract period. Special measures in terms of advancing Phase-C/D procurements are being contemplated in order to meet the ATV launch date of April 2004. The next major milestone is the ATV-CC System Requirements Review (SRR), which is planned for March/April 2001.

The two competitive ATV trainer Phase-B studies are progressing as planned and initial prototyping has started. The contractual issues, relating to the ATV Integration Contract with the RSC-Energia/Gagarin Cosmonaut Training Center (GCTC), have been discussed and an agreement has been reached. A Joint Integrated Simulation Workshop will be held with International Partner, EAC and ATV-CC representatives on 6 - 8 November.

The development of ATV Cargo integration software tools (CARAT) is proceeding as planned. The ITT for the database procurement will be issued to industry in the near future.

Utilisation
Promotion
Preparations are continuing for the global utilisation conference 'ISS Forum 2001', which will be held in Berlin in June 2001. It has been agreed between the partners that greater emphasis should be placed on 'business' aspects, and the programme planning has been adjusted to reflect this.

In the area of Microgravity Applications Promotion (MAP), 44 MAP projects have been approved and significant progress towards completing contract signature for these projects has been made.

The X-38 Orbital Test Vehicle V201 in the Space Shuttle

On 8 September, the International Space Station Virtual Campus was inaugurated. During the coming six months a series of lectures on selected topics relating to the utilisation of the ISS will be held and delivered to a Europe-wide viewing public, via both direct television satellite broadcasting and the Internet.

Accommodation hardware development
The consolidation of the five external payloads to be flown on the starboard side of the ISS as part of the ESA Express Pallet Payload (E2P2) Programme has continued, and work on the five ESA payloads (ACES, SOLAR, EXPORT, EUTEF and FOCUS) is progressing. Due to the delays that NASA is experiencing in its Express Pallet development programme, the first baseline of the user interface is now only expected in early-2001. Following the receipt of an acceptable industrial offer, it is now planned to initiate the Phase-C/D for the European Drawer Rack (EDR) in November 2000.

Astronaut activities
The European Astronaut Centre (EAC) participated in the 'German Space Day', held in Cologne on 24 September, which attracted more than 60 000 visitors. Dr. Uwe Thomas, State Secretary of the German Ministry for Education and Research, visited EAC and delivered an official address.

An amendment to the 1992 Mission Specialist Training Agreement was agreed with NASA in July, extending its duration until July 2001. In recent weeks: EAC and its Russian partners (RSC-Energia and GCTC) agreed on an ATV training concept, with important elements and facilities of ATV training located at EAC, Cologne; ESA and CNES together with their Russian counterparts are in a process of elaborating possible new flight opportunities for European Astronauts on Russian carriers; and ESA Astronaut Thomas Reiter received the 'Space Award 2000' from the Discovery Channel and the 'Verein zur Förderung der Raumfahrt'.

Early deliveries
MPLM Environmental Control and Life Support Subsystem (ECLSS)
Contract closeout is nearing completion. The first two sets of equipment are already integrated into the MPLMs ('Leonardo' and 'Rafaello'), which are at Kennedy Space Center (KSC). The third set is under integration, with the system acceptance and transportation of MPLM-3 ('Donatello') planned for January 2001. The first MPLM flight to the ISS will be in February 2001, to provide subsystems and payload racks for the US Lab 'Destiny', the launch of which is planned for January 2001.

Data Management System for the Russian Service Module DMS-R
The fault-tolerant computer complex installed in the Russian Service Module 'Zvezda' has performed nominally since its launch on 12 July, with the exception of an unexpected event just prior to Service Module docking with 'Zarya'/'Unity'. Investigation of this anomaly by RSC-Energia engineers prior to the actual docking concluded that the problem was in the RSC-Energia applications software.

On flight-day 20 (31 July), the DMS-R computers of 'Zvezda' were successfully integrated with the computers of 'Unity' and 'Zarya', and they took over data-bus control for the entire station. During the subsequent two orbits, NASA and RSC-Energia flight controllers performed a series of tests to verify the end-to-end command capability of the ISS and, since that time, the DMS-R computers, together with the Russian application software, have been responsible for the guidance, navigation and control of the entire ISS.

European Robotic Arm (ERA)
The ERA flight model has been assembled, and delivered to ESTEC in Noordwijk (NL) for structural-qualification and EMC tests. In the meantime, the ERA engineering model is continuing with a programme of functional testing on the Fokker 'flat floor'. Problems with delivered components will necessitate some refurbishment on the flight model following these tests. Although this will not affect the tests' validity, it will delay ERA flight-model delivery.

Hardware for prototype ERA Mission Preparation & Training Equipment (MPTE) has been delivered to ESTEC, and installation and checkout of its software has commenced. Completion of the MPTE and its delivery to Russia is planned for the second quarter of 2001.

The ERA flight model will be ready for delivery in mid-2001. This is consistent with the formally announced launch date for the SPP, on which ERA will be mounted, of October 2002. However, recent information from the Russian Space Agency indicates a further substantial delay in SPP development, and the consequences of this delay are currently being assessed.

Laboratory Support Equipment (LSE)
The qualification testing of all major subsystems for MELFI (-80°C Freezer Laboratory) is in progress.

Dr. Uwe Thomas (centre) in discussion with ESA Astronauts Gerhard Thiele and Reinhold Ewald (in overalls), Jörg Feustel-Büechl (right, Director of ESA's Manned Spaceflight and Microgravity Programme), and Prof. Walter Kröll (left, Chairman of the Board of DLR)

Qualification of the electrical subsystem has been completed and system-level testing started in August and is still ongoing.

Manufacture of critical flight-unit parts of the Microgravity Science Glovebox (MSG) and the integration of the engineering unit are ongoing. The software Interface Control Document (ICD) was finalised in July and the Training Unit was delivered in August.

The data package for the CDR for the Hexapod Pointing System was delivered in July and CDR completion is planned for November.

ISS Exploitation Programme
The Preliminary Authorisation To Proceed (PATP), which is the contractual framework for carrying out the Exploitation Programme Preparatory Phase activities, has been signed off by both Industry and the Executive. An Engineering Change Request (ECR) for the Operations Preparation Definition Phase was released to Industry and a proposal subsequently received. This is currently under evaluation. The RFQs for the Early Activities and overall Operations Contract are in preparation. Issues related to the Executive's proposals for contracting of tasks to the User Centres via the main industrial operations contract, and the roles and tasks of national agency centres in the Exploitation Programme, have been resolved via two separate agreements between the parties involved.

In response to its Call for Interest for commercial-utilisation business developers, the Agency has so far received 14 replies involving circa 40 companies whose interests range from space development, R&D, technology and education, to innovative fields such as media and entertainment. Twelve of the replies contained, albeit often in preliminary fashion, a business proposal either as overall business developer, or as a specific development of a commercial project or sector; the other two were generic manifestations of interest. The evaluation and negotiation of the various propositions is still in progress with a view to generating high-level commitments from companies to support the Executive's proposal on commercial-utilisation policy to the December Council.

Work is continuing in the context of a multilateral ISS Partner working group to agree on common access rules and policies for commercial utilisation throughout the ISS. In addition, pathfinder projects are being set up, each designed to test one or more specific facets of the environment.

Microgravity

EMIR programmes
On 17 September, a contract was signed with Rosaviakosmos for the flight of a 355 kg payload on the Foton-M1 flight in October 2002. On 27 September, the Programme Board for Microgravity (PB-MG) approved the inclusion of the United Kingdom in the EMIR-2 Extension Programme.

Preparations for an ESA parabolic aircraft flight campaign in November 2000 and the Maxus-4 sounding rocket flight in April 2001 have continued. Preparation of the payloads, weighing in excess of 500 kg, to be flown on STS-107 in June 2001 also continued. The facilities being flown on this flight include the Advanced Protein Crystallisation Facility (APCF), the Advanced Respiratory Monitoring System (ARMS), Biobox (a biological incubator), Biopack (a facility for performing biological experiments in microgravity), ERISTO (for research with mammalian cell cultures), and the Facility for Adsorption and Surface Tension studies (FAST - fluid sciences). Preparations have also continued for the launch, also in June 2001, of the first microgravity payload (APCF) to the US Lab.

Microgravity Facilities for Columbus (MFC)
Integration of the system engineering model of the Biolab has been completed. System testing will start in November. Subsystems for the Material Science Laboratory (MSL) and Fluid Science Laboratory (FSL) have been manufactured and the system engineering models will be integrated before the end of 2000. The CDR for the Biolab and the PDR for the European Physiology Modules (EPM) have been successfully completed. The CDRs for the FSL and MSL will be completed by end-2000. Phase-A/B for the Materials Science Laboratory using Electro-Magnetic Levitator (MSL-EML) technology will start by end-2000. esa

The Biolab system engineering model, with ESA Astronaut Claudie Andre-Deshays in attendance

Ariane

Ariane-5 Evolution

One of the most critical elements in the Ariane-5 Evolution Programme is the development and the qualification of the Vulcain-2 engine. So far, three engines have been fired on the test stands in Vernon (F) and Lampoldshausen (D), accumulating 15 400 sec of running up to the end of September. The fourth engine of the six planned started its test on 27 September. The tests so far have shown positive results in terms of solving several problems related to the oxygen turbopump and the nozzle.

The planning has been revised for the first flight of Ariane-5 Evolution from December 2001 to February 2002 due to a soldering problem with the tank bulkhead.

Several reviews of the booster's front and aft skirts have been successfully conducted, confirming the initial technical choices.

Ariane-5 Plus

ESC-A (Cryogenic Upper Stage)

Industry is mainly concentrating its efforts on the integration of the first test model, the so-called 'Modèle Dynamique' or MD, due to start in October 2000. The delivery of the main hardware items is progressing. With the oxygen tank now ready, the hydrogen tank is undergoing final insulation after its structural integration during August.

The Ariane-4 HM7 engine hot-firing-test campaign results have shown that the engine is capable of withstanding the prolonged and more severe working conditions of ESC-A.

The Critical Design Reviews (CDR) for the equipped lines and the hydrogen tank have started. During their corresponding reviews, the designs of the oxygen tank, the oxygen tank damping system and ground coupling plates for ESC-A have shown no major difficulties.

ESC-B (Cryogenic Upper Stage)

An integrated Agency-Industry Working Group is currently elaborating the ESC-B stage architecture, with the aim of meeting the tough performance and cost objectives of the Ariane-5 Plus Programme. The development of the ESC-B Vinci engine has been re-oriented to a purely European development effort following the June ESA Council decision not to pursue the trans-Atlantic co-operation initiative. The first prototype of, and development hardware items for the engine are currently being manufactured.

EPS-V (Versatile Upper Stage)

A hot-firing-test campaign covering the extended utilisation domain and the new nozzle extension for the Aestus engine was successfully performed during the summer.

Vega

The Vega launcher configuration has been updated to include a high-performance, filament-wound solid motor, P80, as the launcher first stage. This change has the dual objective of improving the Vega performance to about 1500 kg into a circular polar orbit at 700 km altitude, and of preparing the technologies required for the next generation of Ariane-5 boosters, using a composite case.

The P80 development is proposed as an additional slice to the Vega Small Launcher Development Programme. Declarations and Programme Proposals for both Vega and the P80 stage are being finalised with a view to subscription by the Member States in November 2000.

The first test firing of the P80 motor is planned for 2003, and the first Vega launch for 2005.

Artist's impression of a Vega launch

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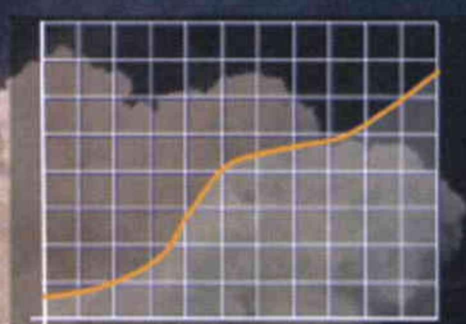
15th ESA Symposium on European Rocket and Balloon Programmes and Related Research



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In Brief

Next ESA Science Programme Director Appointed

At its 147th meeting, at ESA Headquarters in Paris on 19 and 20 October, the Council unanimously elected Prof. David Southwood (UK) as the Agency's new Director of Science from 1 May 2001 for the subsequent four years. Prof. Southwood will take over from Prof. Roger Bonnet (F), who has been ESA's Director of Scientific Programmes since 1984.

Prof. Southwood (aged 55) holds a BA in Mathematics and a PhD in Physics from Imperial College, London. He has spent most of his professional career at Imperial College, apart from two periods at UCLA (University of California, Los Angeles), first as a post-doctoral Fellow and later as a Visiting Professor. He joined ESA for the first time in 1997 as Earth Observation Future Programme Strategy Manager, after which, since April 2000, he has been Regent's Professor at the University of California.

Prof. David Southwood

Prof. Southwood has received numerous awards and honours and has held many Chairmanships during his career, including those of the ESA Science Programme Committee (SPC) and the ESA Space Science Advisory Committee (SSAC). He has also been active both in Europe and in the United States over the years in Public Outreach on Space Science. He has some 200 publications and 100 invited papers to his name.

"David Southwood is certainly one of the most prominent space-science experts Europe has the privilege to have", said ESA's Director General Antonio Rodotà in welcoming Prof. Southwood to his Board of Directors, ...*"and I am sure that, like his predecessor Prof. Bonnet, he will do a really good job for the excellent scientific community that we have in all our Member States"*.

Ulysses Encounters Blustery Weather at the Sun's South Pole

Just as solar storms are brewing, the European-built space probe Ulysses is venturing over the Sun's south pole for the second time in its 10-year life. The intrepid spacecraft passed 70°S on 8 September, shortly before the Sun's 11-year activity cycle is due to peak. Solar storms are already numerous and the high-latitude solar wind (the stream of charged particles blowing away from the Sun) is chaotic and blustery.

Conditions are now very different from those that Ulysses encountered during its first south polar pass in 1994 when solar activity, which is related to the magnetic behaviour of the Sun, was very low. Then, the solar wind at high latitudes was fast, but steady. This latest polar pass gives scientists the opportunity to learn just how different the polar regions of the Sun are at solar maximum compared with solar minimum.

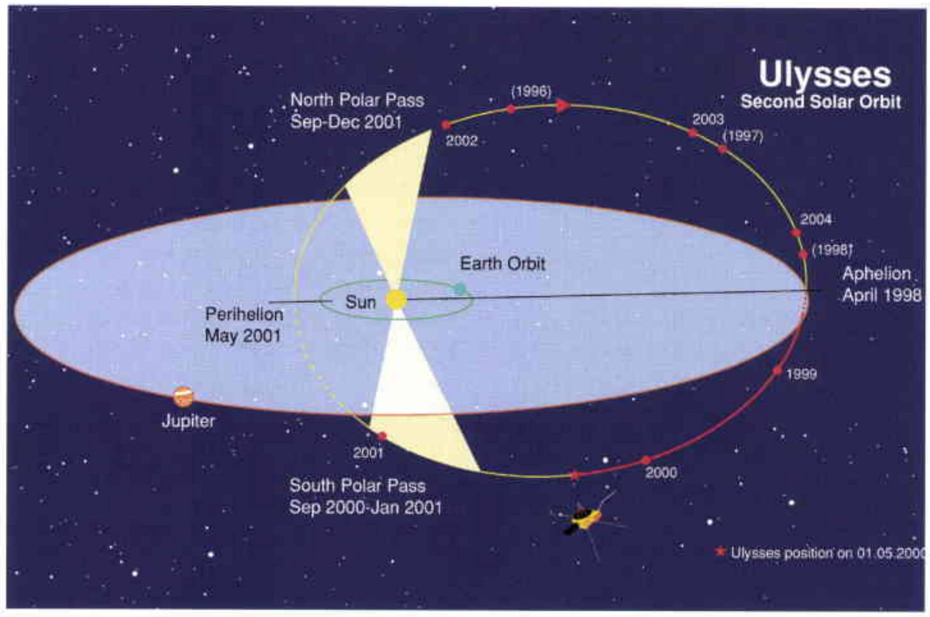
After spending four months above 70°S, Ulysses will swing towards the equator early next year to turn its attention to the northern hemisphere, beginning its passage over the north pole on 3 September 2001. Although it will be travelling the same path that it followed six years ago, conditions will be quite different and new discoveries are eagerly awaited.

Since its launch in October 1990, Ulysses has already proved to be one of the most successful interplanetary missions ever. A joint ESA/NASA undertaking, it is the first spacecraft ever to be launched into an orbit outside the ecliptic, the plane in which the planets orbit the Sun. From this unique vantage point, it has changed our view of the heliosphere, the region of space filled by the solar wind and over which our Sun exerts its influence.

At solar minimum, instruments on board Ulysses found that the fast solar wind, emanating from the Sun's poles, blows at a steady 750 km/s and fills a large fraction of the heliosphere. The state-of-the-art instruments were also able to show that the boundary between the fast wind and the slower, more variable wind from the equatorial regions, is surprisingly sharp. Another surprise was that the effects of collisions occurring at low latitudes between fast and slow wind streams continue to be felt all the way up to the poles.

Ulysses' discoveries, however, have not been confined to the Sun and heliosphere. Instruments on board the spacecraft have also made the first ever measurements of dust particles and neutral helium atoms originating outside the Solar System. These findings have contributed to a major increase in our knowledge about the gas and dust clouds surrounding the heliosphere. Other measurements have led to a better understanding of processes occurring even further away, in distant supernova explosions.

During the relative simplicity of solar-minimum conditions, Ulysses made many surprising discoveries – during the relative chaos and unpredictability of solar maximum, many more are expected. Exciting times therefore lie ahead in our quest to understand the Sun and its heliosphere.



Orbital schematic of Ulysses' south polar pass

A Brochure (ESA BR-168) issued to celebrate Ulysses' first ten years in orbit, and which contains further details on the mission's exciting discoveries to date, is available from ESA Publications Division.

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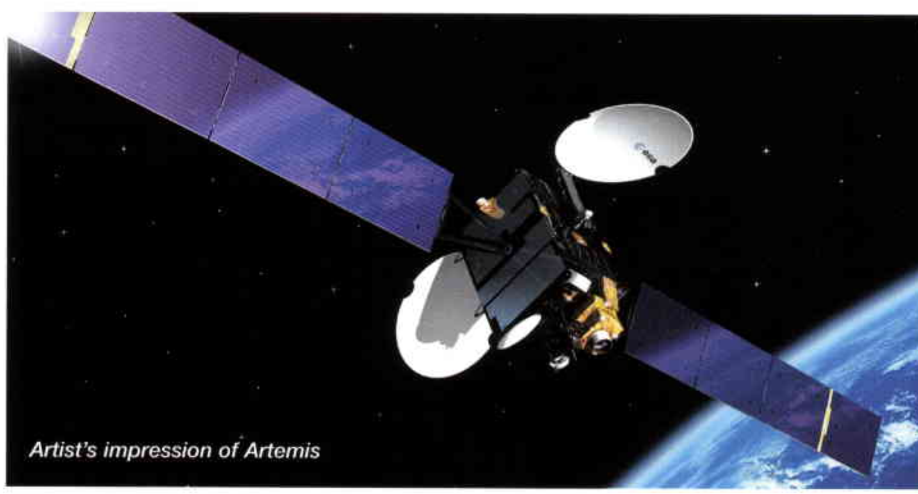
Artemis, Europe's Latest Communications Satellite, on Display at ESTEC



Artist's impression of Artemis

ESA's advanced communications satellite, Artemis, is currently undergoing a final series of functional checkout tests at ESTEC in Noordwijk (NL).

Artemis is not the conventional type of communications satellite. In particular, it differs in one very important aspect: none of its payloads connects a fixed point on the Earth with other fixed points on the Earth. Instead:

- Artemis will connect users on the ground with satellites in orbit via its radio-frequency data-relay payload. This dramatically increases communication time with spacecraft in low Earth orbit (LEO). For instance, a scientist anywhere in Europe will be able, via Artemis, to monitor the status of an experiment on the International Space Station in real time and actively intervene. This payload will also enable ESA's next Earth-observation satellite Envisat, slated for launch in June 2001, to transmit its data to the ground in real time.
- Via its optical data-relay payload, SILEX, Artemis can receive and re-transmit in real time images taken by Earth-observation satellites such as the French Spot-4. Data communication between satellites using an optical link (laser pulses) is a novelty in space and offers great advantages over conventional radio-frequency systems.
- With Artemis, a mobile user will be able to link up from anywhere in Europe, North Africa or the Middle East to any fixed user in the same area at very competitive prices. Large ocean areas are included in Artemis' coverage zone, allowing voice or data connections to land from the Mediterranean, the North Sea or the eastern part of the Atlantic Ocean.
- The navigation payload will enable users to determine their position with higher accuracy and 24-hour availability. Artemis will add corrections and health checks to the existing GPS signals, thus supporting the first phase of Galileo, Europe's new navigation programme.

In addition to these many novel communication services, Artemis will provide European industry with opportunities to gain in-orbit experience with advanced technologies. The most prominent of these is the ion propulsion system, the very high power-to-mass ratio of which helps to reduce launch costs and increase satellite lifetime.

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Caring for Planet Earth: Europe's Latest Space Capabilities Presented in Gothenburg

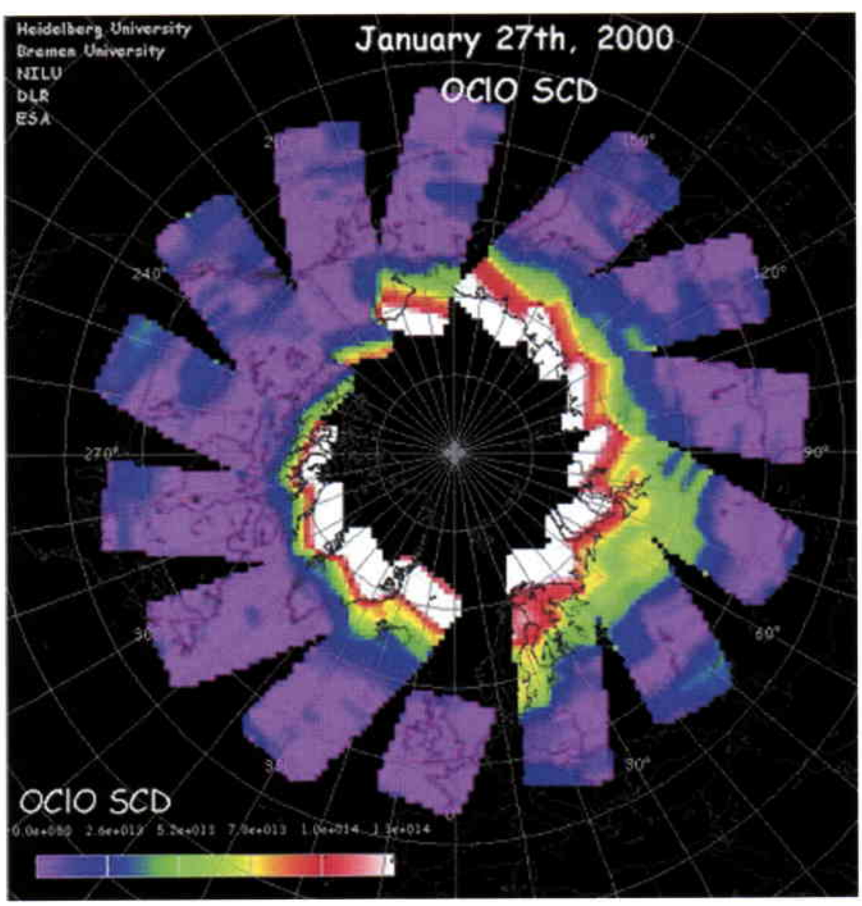
The ozone layer, protecting our planet from potentially harmful ultraviolet sunlight, is threatened by human activities, in particular the steady release of chlorofluorocarbons (CFCs) into the Earth's atmosphere. In 1987 the leading industrial countries signed the Montreal Protocol in which they agreed to phase out the products responsible for ozone depletion. In April 1995, with the start of operation of the GOME instrument, an optical sensor on board its ERS-2 satellite, ESA opened a new chapter in ozone monitoring. GOME's higher spectral resolution and broader wavelength coverage enable it to measure the levels of ozone, and several other trace gases also, much better than previous instruments. A 50% ozone loss in the lower stratosphere was observed over the Arctic for short periods this spring, and a record increase in the size of the ozone hole over the Antarctic has been detected in recent months.

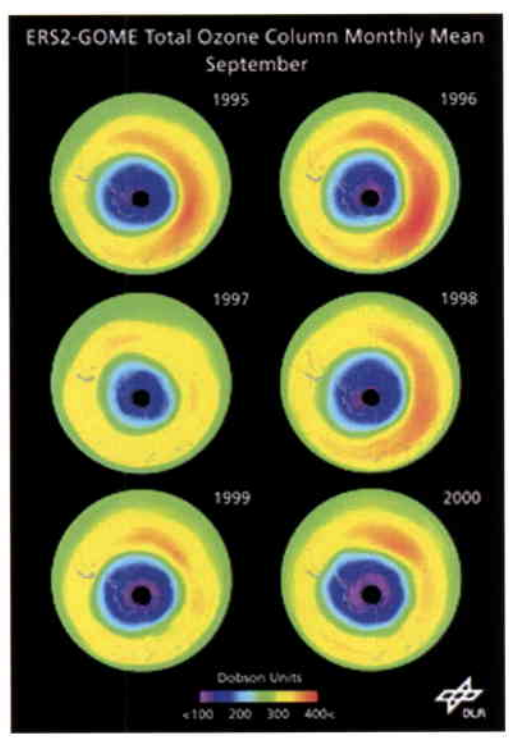
The latest scientific results and possible future applications based on GOME measurements were presented at an international gathering organised by ESA and Chalmers University – 'The ERS/Envisat Symposium -Looking Down to Earth in the New Millennium' – in Gothenburg, Sweden, from 16 to 20 October. It included more than 400 presentations (talks and posters) by World experts – scientists, remote-sensing experts and industry representatives – in more than 40 sessions covering the scientific results and applications of ESA's ERS missions.

It also presented the Agency's Envisat mission, to be launched in June 2001, which is designed to build on the ERS groundwork and to make a major contribution to global environmental monitoring. ESA has already received some 700 project proposals from the World's scientists designed to exploit this unique and valuable data source. In Gothenburg, ESA also presented its in-orbit commissioning plan for the calibration of Envisat's instruments and the validation of the derived data products. Over 100 scientific groups are supporting ESA in the preparation and execution of this commissioning phase. ESA's new commercial distribution policy for Earth-observation data was also presented, along with the Agency's overall strategy for Earth-observation activities and future mission plans.

The data gathered by the ERS missions continue to make important contributions to environmental monitoring and our understanding of the physical and chemical processes underlying Earth's systems, on both the global and the local scale. By integrating ERS data with local information from other sources, national authorities and operators have a powerful tool for environmental monitoring, and valuable information for planning and preventive actions. The transition from ERS to Envisat is being managed in such a way as to ensure continuity in the provision of this key environmental information; once it is completed, a stream of new data will become available for oceanographic and atmospheric studies, with particular emphasis on marine biology and atmospheric gases and aerosols

The Gothenburg event was attended by some 550 participants, representing the scientific community, operational and commercial users, and service providers, who relished this unique opportunity to appraise the state of the art in ERS applications and explore the imminent potential of Envisat. esa





Changes in the ozone hole over the Antarctic during the last 6 years, measured by GOME

GOME measurements of chlorine activation over the Arctic

Luxembourg Strengthens Its Ties with ESA

On 12 September, Mrs Erna Hennicot-Schoepges, Minister for Culture, Higher Education and Research of the Grand Duchy of Luxembourg, and Mr Antonio Rodotà, ESA's Director General, signed an Agreement that will enable Luxembourg to participate in ESA's ARTES telecommunications programme.

A member of the European Union and the Council of Europe, Luxembourg has already acquired experience in space matters through its involvement in Intelsat, Eutelsat and EuroControl, and through its national activities linked to space. With this Agreement, the European dimension of the Grand Duchy's space activities has been further reinforced.

The Advanced Research in Telecommunications Systems programme ARTES consists of several elements covering particular areas of telecommunications, such as on-board processing, multimedia/global information infrastructures, advanced mobile systems, tele-education, tele-medicine, tele-conferencing, and data exchange. Its overall aim is to improve the competitiveness of European industry on world markets for communications missions, and to promote new services for advanced communications systems. ARTES also provides support to other applications programmes, such as navigation and Earth observation.

After the signing ceremony, Mrs Hennicot-Schoepges and Mr Rodotà held a Press Conference for the assembled journalists.

Towards a European Strategy for Space Technology - *The Joint ESA/CDTI/Eurospace/EC Workshop on European Strategy for Space Technology*

The ESA Technology Programmes Department, in cooperation with the European Commission, Spain's Centro para el Desarrollo Tecnológico e Industrial (CDTI) and Eurospace (representing the interests of European space industry), were the joint organisers of a 'Workshop on European Strategy for Space Technology', which took place in Seville, Spain, on 21-23 May.

The opening session provided an overview of the space-technology scene in Europe and the strategy for European Space Technology, as an integral component of the European strategy for space. Among the speakers, A. Rodotà, ESA's Director General, presented the development process for and current status of the European space strategy, and H. Allgeier, Director General of the European Commission's Joint Research Centre (ISPRA), elaborated on the interests and role of the European Union in space.

The four main sessions of the Workshop focussed on:
- The Role of Technology
- Establishing the Strategy
- A European Space Technology Master Plan
- European Plans and Activities in Space Technology.

There was also a Round Table to solicit and discuss the views of industry. A general overview by the Chairman of Eurospace's R&D Group prepared the way for a lively discussion on industry's perception of and interest in space technology research, development, procurement, alliances and related issues.

The Workshop concluded with a Panel Discussion chaired by H. Kappler and H. Allgeier. The participants made a number of recommendations and proposals on technology-related issues, to be included in the ESA policy document.

Some 150 participants, including ESA Industrial Policy Committee (IPC) delegates, representatives of the European Commission, operators, and industry, and representatives from the ESA Directorate of Industrial Matters and Technology Programmes and other ESA Directorates, took part in the various sessions.

The participants agreed that Europe has to unify and coordinate its space-technology activities through a coherent European policy, and endorsed a position paper on a European strategy for space technology, the principal objectives of which should be:
- implementation of a technology specialisation policy, supported by networks of centres of excellence and targetting innovative products
- increased synergy with and application of highly innovative non-space technologies from other areas, such as the defence sectors and information technology
- greater involvement of industry in the R&D decision-making process for public technology programmes, and increased R&D emphasis on new markets and new users by co-funding activities with industry where commercial potential exists
- closer collaboration between industry, academia and research centres in the area of pilot development work, in partnership with space agencies, commercial companies and financial institutions
- preservation and reinforcement of skills, experience and know-how at individual-company level, and
- re-appraisal of the technology objectives of industry in the wake of the major

The Panel Discussion on the Role of Technology in progress in Seville (E) industrial restructuring taking place throughout Europe.

Led by ESA, the current approach to the European Strategy for Space Technology designed to achieve the above objectives is based on:
- Identification of technology needs and priorities for European programmes, strategic areas for European independent capabilities and leadership, and the competitiveness of European industry in the short and long term (Dossier 0).
- Acquisition of a complete overview of all relevant technology-development activities in Europe and the relevant skills, specifically at European and national level, and including industry and academia (Mapping, ESA Technology Master Plan and National Technology Master Plans).
- Definition of implementation guidelines and joint funding for the necessary technology R&D activities, harmonised through a coherent and co-ordinated European Space Technology Master Plan (ESTMP), which will include selected concerted development programmes.

Technology harmonisation is a basic prerequisite for the preparation of the ESTMP. The principal purpose of this harmonisation process is the specialisation of skills and the strengthening of industrial cooperation. Pilot cases for harmonisation are being discussed for selected technologies (such as synthetic aperture radar, solar arrays and electric propulsion). Items for discussion include the identification of possibilities for sharing skills, expertise, capacities and resources by networking between specialised centres, and opportunities for sharing objectives and risks with potential partners. An assessment is being conducted for each technology included in the ESTMP. This is directed in particular at such issues as maturity, target readiness, competitive impact and competitive position.

As a conclusion to the Workshop, the participants expressed their strong support for the European strategy on technology R&D as implemented by ESA. They expect this strategy to produce a significant improvement in the efficiency and effectiveness of European space-technology R&D.

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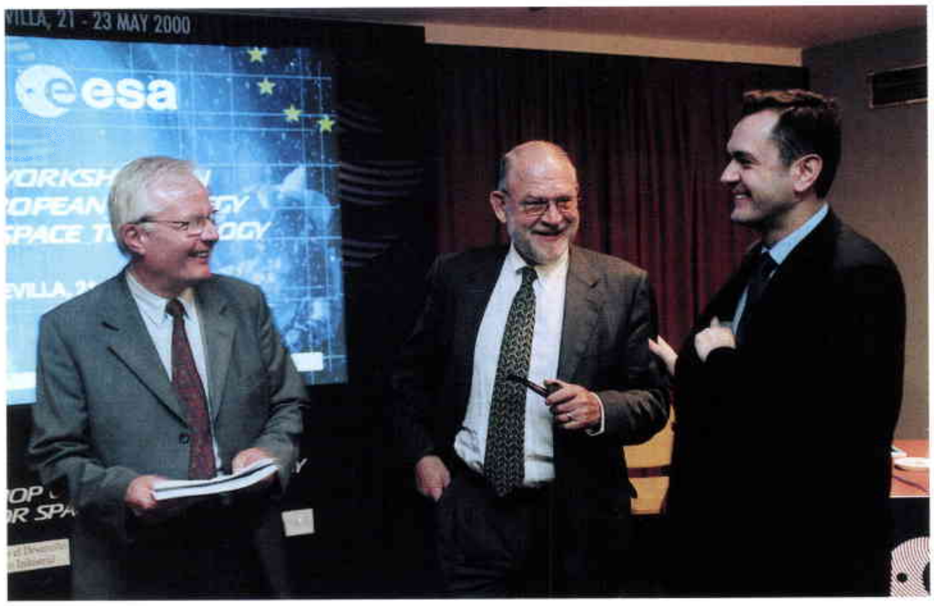


From left to right: H. Kappler, ESA's Director of Industrial Matters and Technology Programmes; H. Allgeier, Director General EC Joint Research Centre; and and J.M. Leceta, CDTI, discussing Technology Strategy

ESA's Virtual Campus for the International Space Station

ESA inaugurated its Virtual Campus for the International Space Station on 8 September at ESTEC, in the presence of leading European scientists and industrialists, ESA's Director General, Antonio Rodotà, and the Director of Manned Spaceflight and Microgravity, Jörg Feustel-Büechl.

The Virtual Campus will be the main European source for validated information on the International Space Station (ISS) and its utilisation. It will be a forum where present and future users of the Station can share their knowledge and find new partners. The 'campus' is managed and operated by the ISS User Information Centre, located at ESTEC. It is open to the whole European space community.

As a resource centre, the Virtual Campus will provide ISS information and advice. It will explain the various experiment facilities of the Station's pressurised laboratories available to European scientific researchers, development engineers and service providers. It will not only focus on the technical aspects of Station utilisation, but also help interested users to find scientific, operational, financial and political support for their experiments.

Through the Virtual Campus, users can build contacts with the engineers in European industry and space agencies who are working on the development and operation of the European research facilities. They will also be able to establish links with the programme managers and scientists at ESA and at the national space and research organisations in Europe who are involved in the strategic planning and the attribution of resources and access rights for Station utilisation.

The Virtual Campus will bring the ISS closer to the European space community at large and to political decision-makers, the media and the general public in Europe. Video and audio live transmissions from the Station, the launch and landing sites, and the astronaut training centres will be broadcast via direct satellite TV and Internet streaming video. Interactive information sessions will involve the audience via telephone and Internet. The information programme will be complemented by Internet chat sessions and by interactive virtual-reality tours of the Station via satellite television and Internet.

The Virtual Campus will broaden the audience for the research conducted aboard the Station, with other spacecraft and in ground facilities. It will organise regular lectures on scientific, technological and application-

Inauguration of the Virtual Campus at ESTEC in September

oriented aspects of Station utilisation, presented by scientists who have proposed experiments for the Station. They will also be transmitted live via direct satellite TV and as streaming video on the Internet. Initially, these lectures will be held in the auditorium of the User Information Centre at Noordwijk, which is equipped for TV recordings, satellite transmission and Internet communications. Over the coming months, the User Information Centre will acquire the equipment and expertise for transmitting lectures as streaming Internet video directly from the various research institutes and industrial laboratories involved in Station utilisation.

Particular efforts will also be made to distribute the knowledge already gained by scientific experimentation and technology demonstration in other projects such as Spacelab, Spacehab, Foton, sounding-rocket flights, parabolic aircraft campaigns, drop towers and ground laboratories. ESA's Microgravity Data Base (accessible at *http://www.esa.int/cgi-bin/mgdb*) is the starting point. It will be made more user-friendly for the general public and will evolve into a general database on scientific results from Station research.

The Virtual Campus will offer its infrastructure for establishing Virtual Institutes in scientific disciplines that can benefit from the Station research facilities. The Virtual Institute for Health Care is the first planned; others might follow.

Using the campus, ESA will publish the announcements for space research opportunities and for ground research opportunities that could be used for preparing future Station experiments. Users can receive additional information and advice to help them in responding and in developing their experiments.

The campus will play an important role in building up joint research teams by giving users access to the information available at ESA on planned and intended research and applications themes of other users. Within the Microgravity Applications Programme, ESA has already introduced the idea of 'Topical Teams' in which fundamental researchers from academia are teaming up with more application-oriented researchers from industrial laboratories to work on topics of common interest which often have a commercial perspective. A significant number of Topical Teams have already been created and more are expected.

The Internet site of the Virtual Campus is at: *http://www.spaceflight.esa.int/virtualcampus*

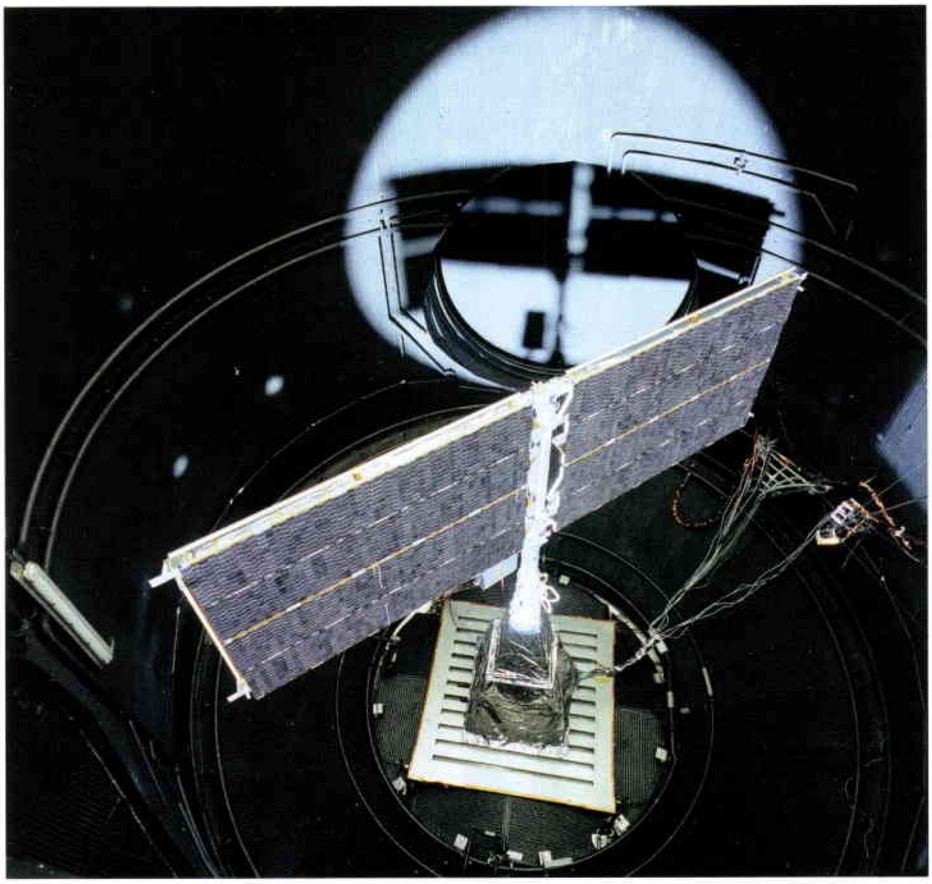
Ariane Launches

The 131st Ariane launch (V131) took place successfully on Thursday 17 August 2000 at 8:16 p.m. Kourou time (11:16 p.m. GMT). An Ariane-44LP equipped with two liquid-propellant strap-on boosters lifted off from the Guiana Space Centre to put two telecommunications satellites, Brasilsat-B4 and Nilesat-102, into geostationary transfer orbit (GTO).

The 132nd launch (V.132) took place successfully on Wednesday 6 September 2000 at 7:33 p.m. Kourou time (10:33 p.m. GMT), when an Ariane-44P, with four solid strap-on boosters, put the Eutelsat telecommunications satellite W1 into orbit.

The Ariane-506 launch (V.130) took place successfully on Thursday 14 September at 7:54 p.m. Kourou time. This time an Ariane-5 lifting-off from the European Spaceport in Kourou placed the two telecommunications satellites Astra-2B, for the Société Européenne des Satellites (SES), and GE-7, for American operator GE Americom, into geostationary transfer orbit.

Hubble's New Solar Arrays being Tested at ESTEC

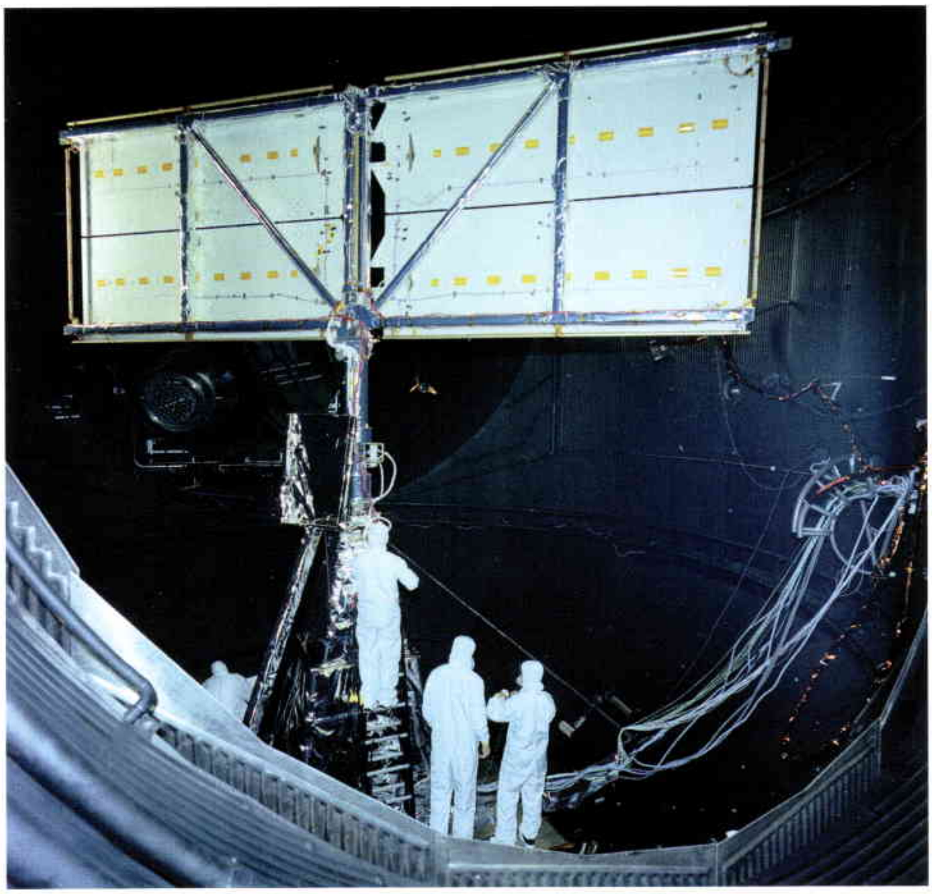


Hubble Space Telescope's solar array under test in the Large Space Simulator (LSS), at ESTEC, Noordwijk (NL)

In mid-October, at ESTEC in Noordwijk (NL), a team drawn from ESA and NASA began a unique and difficult test on one of the Hubble Space Telescope's new solar-array panels. Two of these panels will be installed by astronauts in November 2001, when the Space Shuttle Columbia visits Hubble on a routine servicing mission. The test will check the mechanical integrity of the new arrays before they are installed in orbit.

Hubble orbits the Earth once every 90 min, during which the telescope experiences 45 min of searing sunlight and 45 min of freezing darkness. The tests at ESTEC will detect any tiny vibrations, or 'jitter', caused by these dramatic and cyclic changes in temperature. Even a small amount of such jitter can affect Hubble's sensitive instruments and interfere greatly with observations.

Hubble's first set of solar arrays did experience mild jitter of this sort and were replaced in 1993 with a much more stable pair. Since then, advances in solar-cell technology have led to the development of even more efficient arrays. Despite being smaller, therefore, this new set of arrays generates more power than the previous pairs. Unlike the earlier sets, which roll up like window blinds, the new arrays are rigid, using an advanced structural system to support the solar panels.

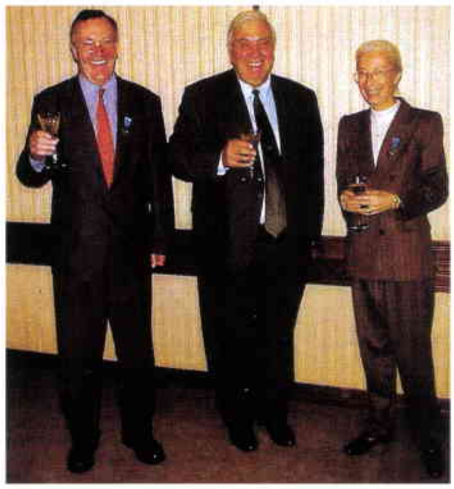


Because of the size of the new arrays and the requirement to conduct the testing on a seismic foundation to ensure a 'quiet environment', the Large Space Simulator (LSS) at ESTEC is the only facility in the World that can perform the tests. ESTEC has long-standing experience with Hubble's solar arrays, in that ESA provided Hubble's first two sets, and has built and tested the motors and electronics for the new set. This latest test is therefore another chapter in an enduring partnership between ESA and NASA on the Hubble Space Telescope.

The LSS facility features a huge vacuum chamber containing a bank of extremely bright lights that simulate the Sun's intensity – including sunrise and sunset. By exposing the solar-array wings to the light and temperature extremes of Hubble's orbit, the ESA and NASA engineers can verify how the new set of arrays will perform in space.

ESA Receives Russian 'Blue Planet Award'

In recognition of the excellent and long-standing cooperation between the Russian space agency, Rosaviakosmos, and ESA, on 17 October in Moscow Mr Yuri Koptev, Director General of Rosaviakosmos, handed over the 'Blue Planet Award' to Mr Jörg Feustel-Büechl, ESA's Director of Manned Spaceflight and Microgravity, and Mrs Karin Barbance of ESA's International Relations Department.



From left to right: Jörg Feustel-Büechl, Yuri Koptev and Karin Barbance

One Telephone Call Mobilises Space Facilities for Natural-Disaster Management

From 1 November, countries that have suffered a natural or technological disaster will be able to get emergency assistance from the space facilities of ESA, CNES and the Canadian Space Agency (CSA) by simply calling a single telephone number available now to authorised users. As soon as a natural disaster occurs, they will be able to call an operator at ESRIN (ESA's establishment in Frascati, Italy), who will immediately contact the duty engineer at ESA, CNES or CSA. That engineer will then deploy the appropriate space facilities belonging to the three agencies to assist the country in which the disaster has struck: earth-observation data from ERS (and soon Envisat), Spot and Radarsat, facilities for telemedicine and navigation (e.g. to track buoys marking an oil slick), ground infrastructures and archived satellite imagery. The forthcoming Artemis and Stentor communication satellites will also be available to relay data directly to the country concerned.

When called upon for help in a crisis, the three agencies will designate a single project manager to liaise with the country that is affected. Assistance will not be confined to supplying the satellite data, but will also include its processing and professional interpretation.

The decision to set up this 24-hour hotline was taken on 25 October, at the second meeting of the Board of the International Charter on Space and Major and Disasters. The Charter was signed on 20 June this year by ESA and CNES, with CSA subscribing on 20 October. It is a far-reaching initiative to promote cooperation by space-system operators in mitigating the effects of natural or technological disasters. Under the Charter, which is open for signature to satellite operators anywhere in the World, all partners undertake to cooperate on a voluntary basis, with no mutual exchange of funds.

Arrival of First ISS Expedition Crew

The permanent occupation of the International Space Station (ISS) began on 2 November with the arrival of the first 3-man crew. The docking followed the flawless launch of the Soyuz spacecraft at 07:53 UT on 31 October from the Baikonur Cosmodrome in Kazakhstan.

The Expedition 1 crew of Station commander Bill Shepherd (US), Soyuz commander Yuri Gidzenko (Russia) and flight engineer Sergei Krikalev (Russia) will work aboard the Station until their Expedition 2 replacements take over next February.

This first crew's arrival is not only an historic moment for mankind, but also for Europe because their mission success involves elements provided by ESA. For example, they will install the Control Post Computers of the ESA-provided Data Management System, which is the 'brain' of Russia's Zvezda service module and of the entire early ISS.

The astronauts will also unload a Progress supply vehicle, planned for launch on 1 February 2001, carrying the electronic unit for the European Global Time System (GTS) experiment and mount it inside Zvezda. GTS will allow the synchronisation of radio-controlled clocks and watches from space and, in the longer term, the disabling of stolen cars and credit cards.

During their 4-month tenure, the crew will host three visiting Shuttle crews delivering the first large solar arrays, the Destiny US Laboratory, Destiny's first science racks and the first Italian-built Multi-Purpose Logistics Module (Leonardo).

Umberto Guidoni will be the first ESA astronaut aboard the ISS as part of the Shuttle STS-102 mission in April 2001.

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EARTH-OBSERVATION QUARTERLY NO. 66, INCL. RECORD OF IMAGES (NOVEMBER 2000)
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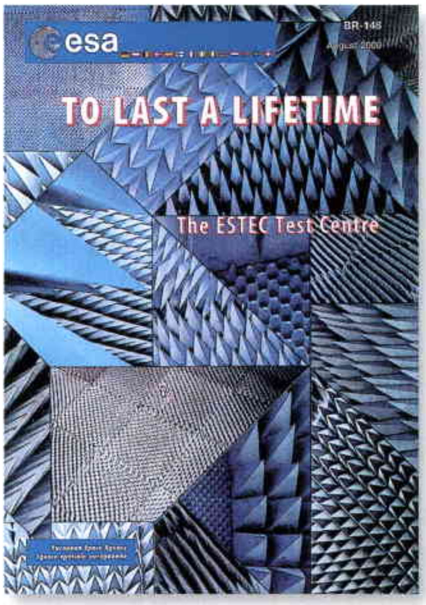

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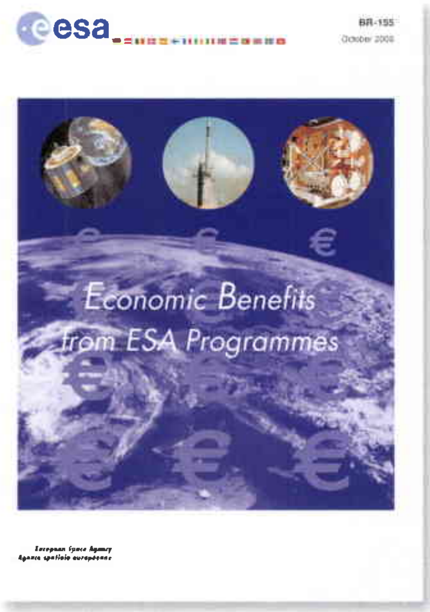

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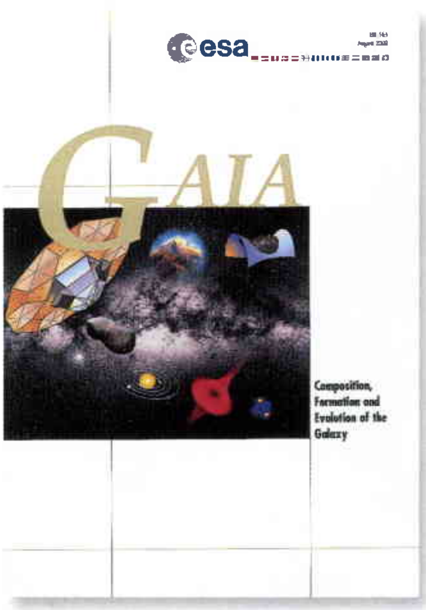

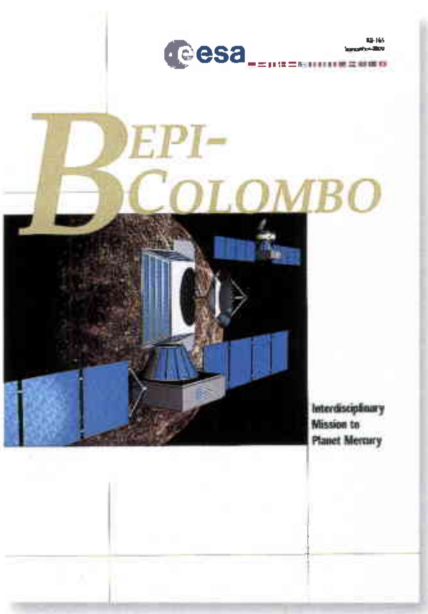

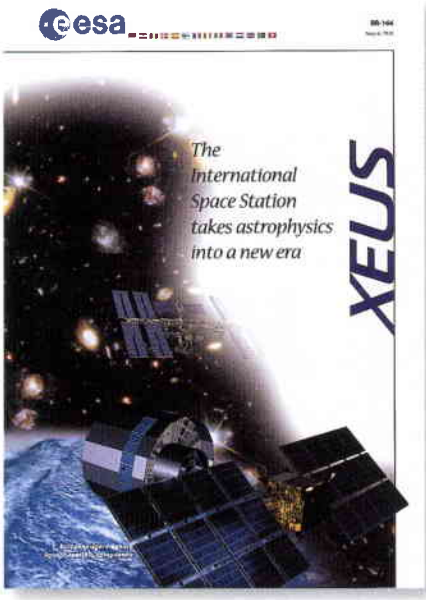

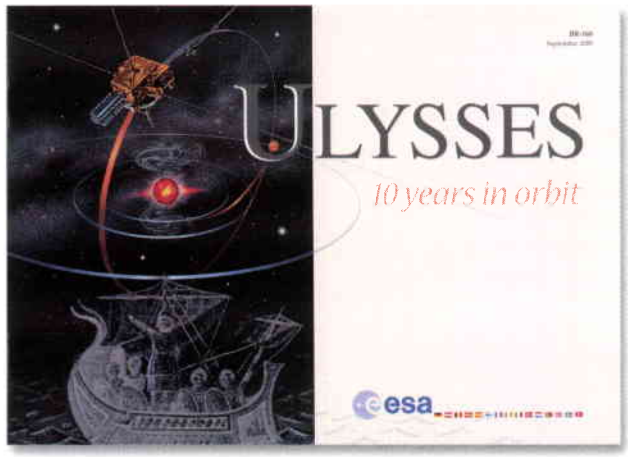

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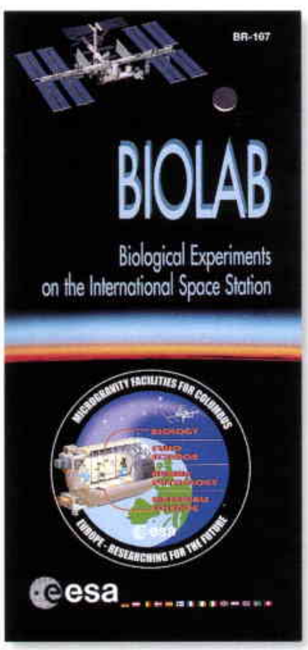

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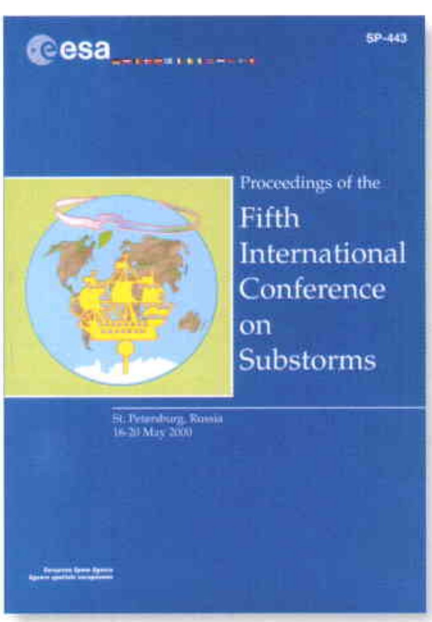

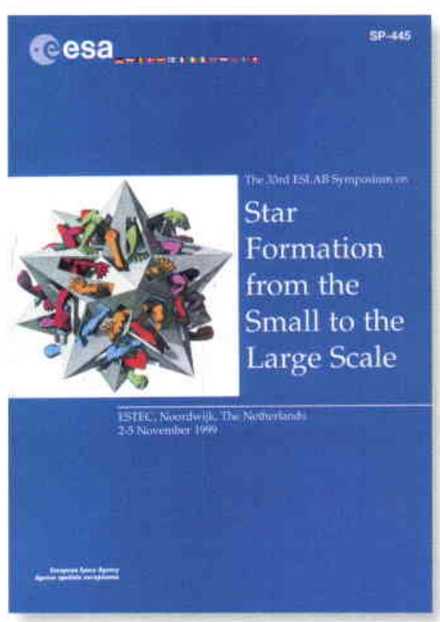

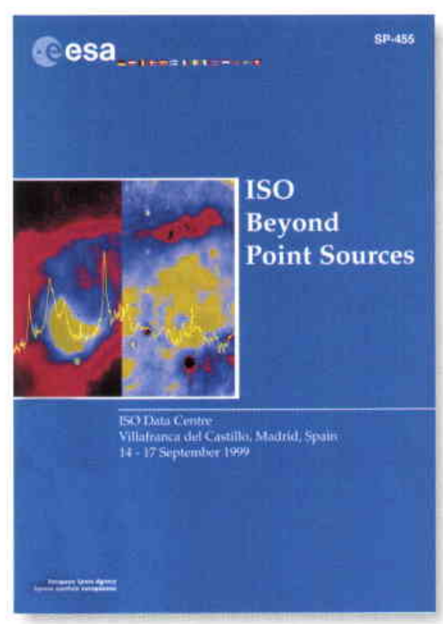

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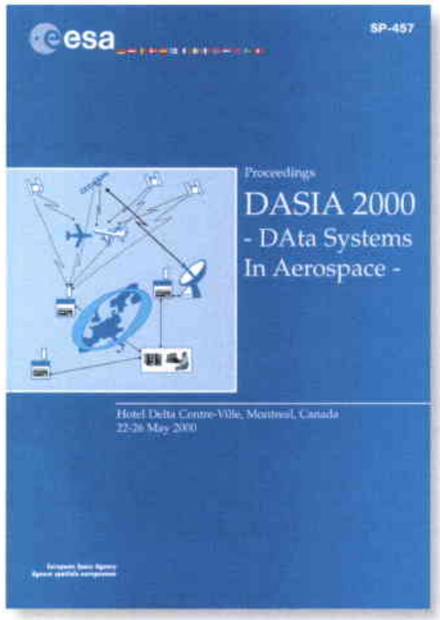

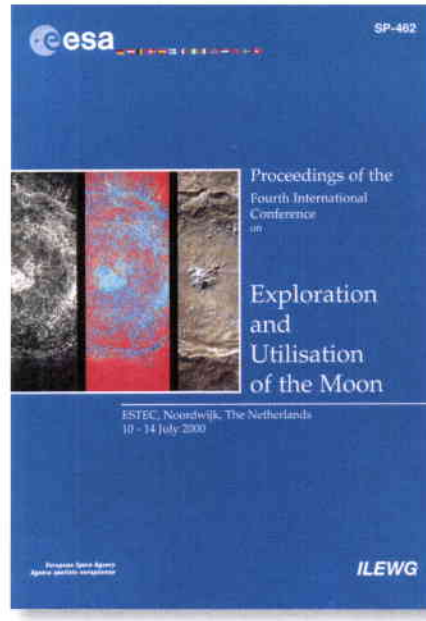

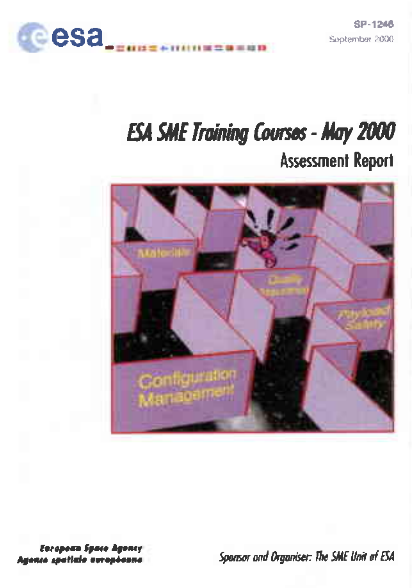

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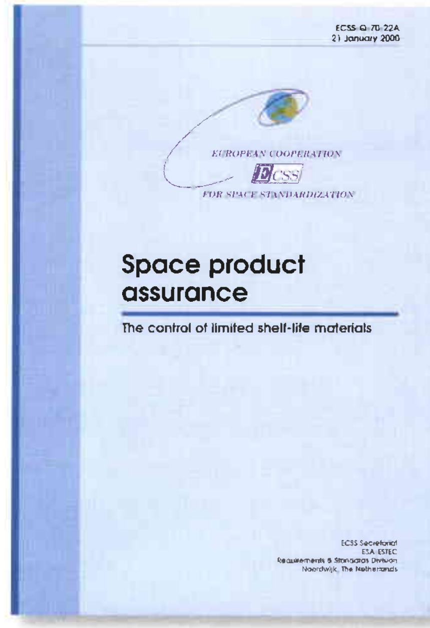

Announcement of Research Opportunities in Life Sciences and Space Science

In the second half of 2002, the European Space Agency (ESA) will fly a scientific payload on the Russian recoverable satellite Foton M-1. The spacecraft will carry equipment to accommodate exposure experiments of two different types:

1. exposure to the harsh space environment ("Biopan"),
2. exposure to the reentry environment ("Stone").

ESA announces an opportunity for proposing experiments in the field of exobiology for Biopan and Stone. Proposals in the fields of chemical evolution, meteoritics, geochemistry, radiation biology and radiation dosimetry will also be considered. Send your proposals to:

Secretariat, MSM-GAL, ESTEC

mail address:	e-mail address:	fax number:
Keplerlaan 1 NL-2201 AZ Noordwijk	msmlife@estec.esa.nl	(+31) 71.565.3661

The closing date for submittal of proposals is 19 January 2001

Biopan

ESA's Biopan is a pan-shaped container for exposure experiments in space. In orbit, Biopan is opened to expose the test samples to space vacuum, solar UV and space radiation, or a selection thereof.

Stone

Experiment samples can be mounted in the skin of the reentry capsule of the Foton spacecraft to test the effects of atmospheric entry on mineralogical and biological materials ("artificial meteorites").

Information on this Announcement is available via the Internet at:

http://www.spaceflight.esa.int/biopanstone

This announcement is coordinated between the Directorate of Manned Spaceflight & Microgravity and the Directorate of Science. These research opportunities are also open to non-ESA member states.

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