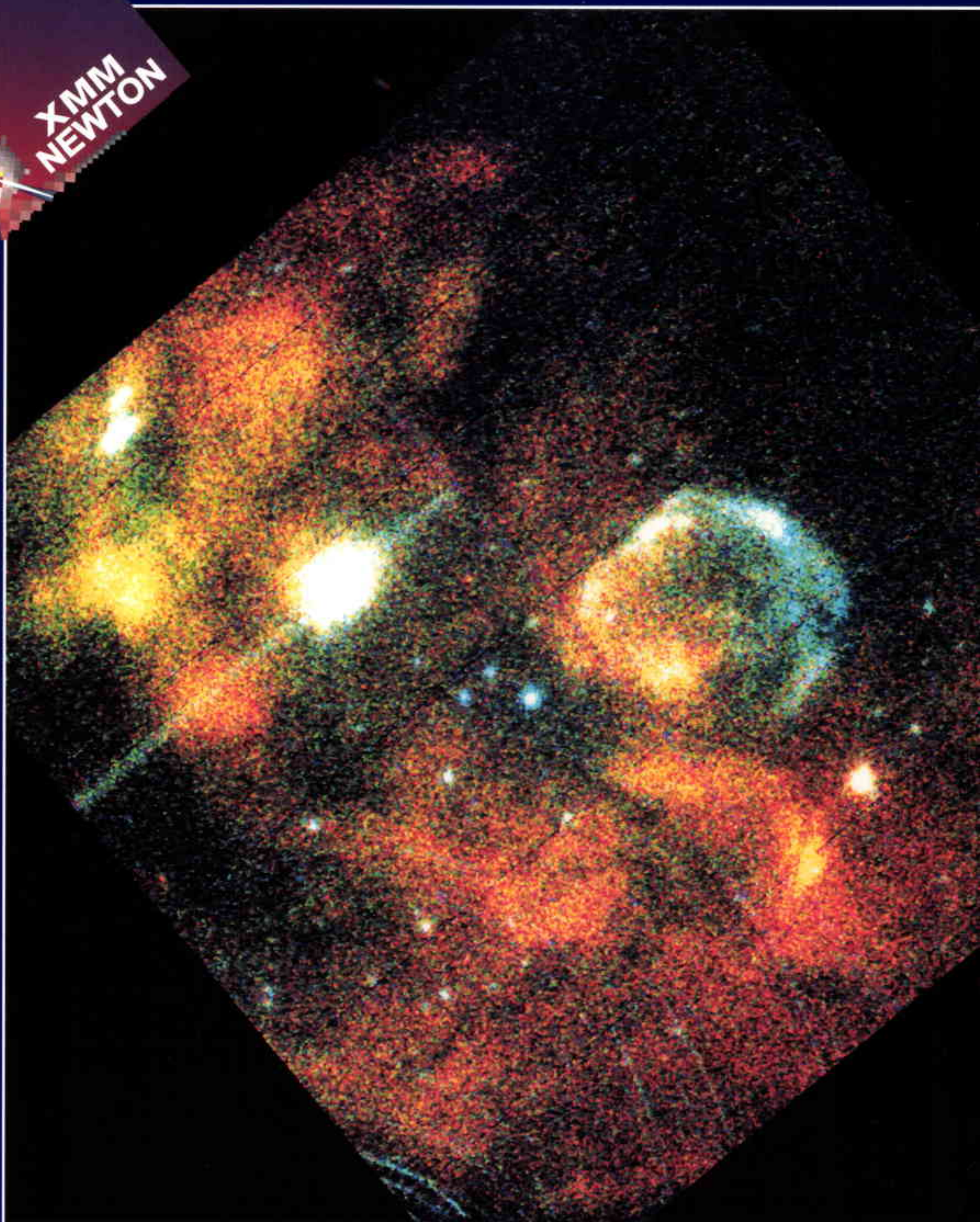
esa bulletin

number 101 - february 2000



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Agence spatiale européenne

european space agency

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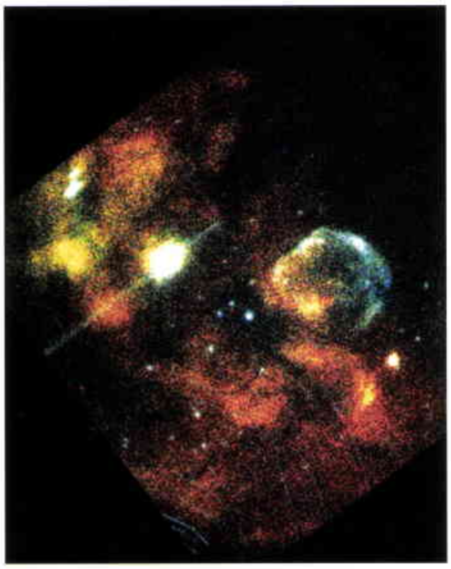

Cover: X-ray temperatures in the Large Magellanic Cloud, as revealed by XMM's EPIC-PN camera (see page 135 of this issue)

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10-15 September 2000 Sorrento, Italy

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The Symposium intends to provide a forum for scientists from academia and industry to present and discuss recent advances in their research on gravity-dependent phenomena in Physical Sciences and Biotechnology. Results originating from theoretical work, numerical modelling, ground-based and flight investigations are solicited. The major topics include Fundamental Physics, Fluid Physics, Heat and Mass Transport Phenomena, Physical Chemistry, Fluid Thermodynamics, Thermophysical Properties of Fluids, Combustion, Solidification Physics and the Crystallisation of Inorganic Materials and Biological Macromolecules. Topics in Biology and Bioengineering, which are expected to benefit from cross-fertilisation and synergy with physicists, such as multi-phase flows and surface physical chemistry, including structured deposition of macromolecules, will also be addressed.

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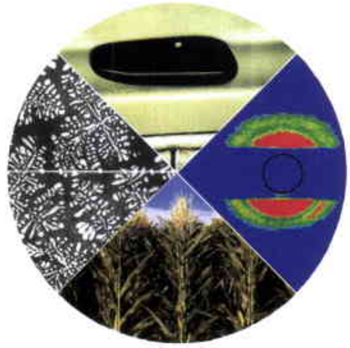

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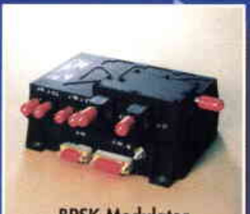
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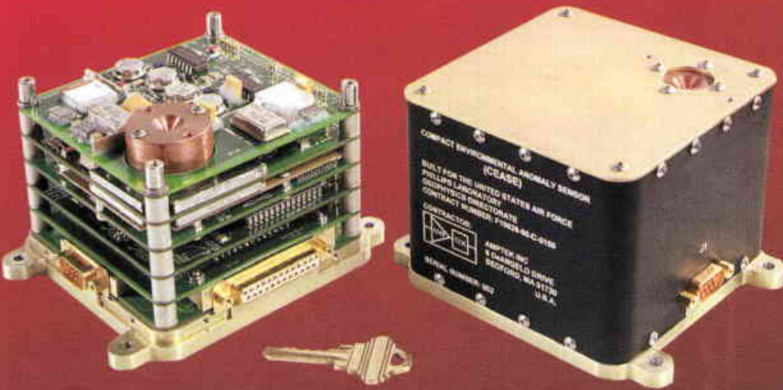

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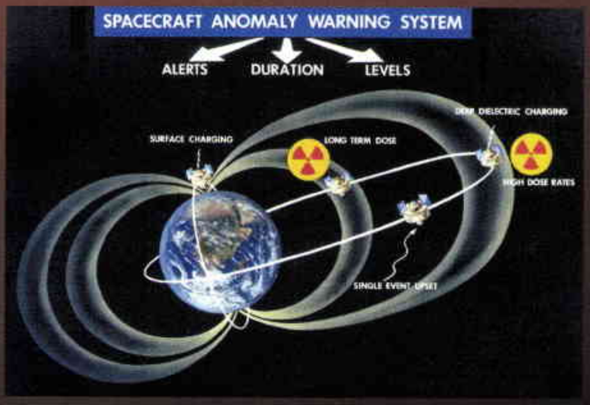

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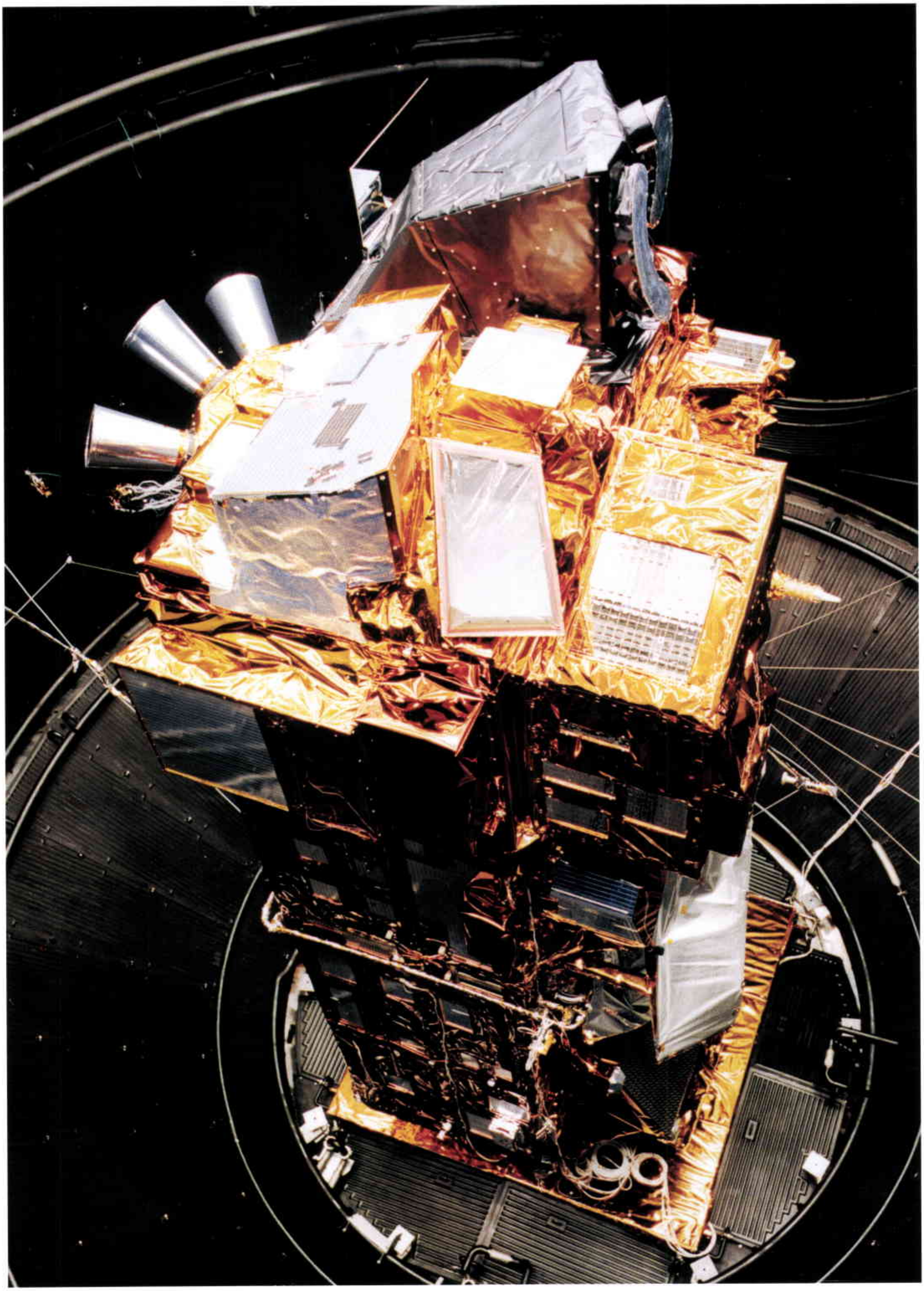


MIPAS – An Envisat Instrument for Atmospheric Chemistry and Climate Research

M. Endemann, P. Garé, J. Langen, H. Nett & C.J. Readings
ESA Directorate for Applications Programmes, ESTEC, Noordwijk, The Netherlands

MIPAS, the Michelson Interferometer for Passive Atmospheric Sounding, is a high-resolution Fourier-transform spectrometer designed to measure concentration profiles of atmospheric constituents on a global scale. It will observe the atmospheric emissions from the Earth's horizon (limb) throughout the mid-infrared region, which will allow the simultaneous measurement of more than 20 atmospheric trace gases, including the oxides of nitrogen and several chlorofluorocarbons (CFCs). Of these, the five major species, as well as pressure and temperature profiles, will be routinely retrieved by the ESA ground segment. These MIPAS data will provide global data coverage, including in particular the polar regions, where the stratospheric chemistry is currently exhibiting some alarming changes.

Scientific rationale

The past decade has seen increasing public concern about the Earth, its environment and mankind's impact on it. Global threats such as climate warming, stratospheric ozone depletion, tropospheric pollution etc. have demonstrated the need to develop a much better understanding of the Earth system and the role of the atmosphere. In many areas knowledge is woefully lacking despite its relevance to the development of climate models and numerical forecasting.

In considering the way forward, it is important to realise the need to study not only the lower atmosphere (or troposphere), but also the other layers of the atmosphere, namely the stratosphere and the mesosphere. All layers are important and to progress it is essential to study all three. Despite their importance, the processes (dynamic as well as chemical) controlling the levels of trace species and their distribution in the atmosphere are far from understood.

The basic requirement is for data to identify processes, to formulate models to represent these processes, to validate the models, and to monitor levels of key geophysical variables.

Responding to this need for data, the ESA Envisat mission (Fig. 1) includes three chemistry experiments, namely GOMOS (Global Ozone Monitoring by Occultation of Stars), SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography) and MIPAS (Michelson Interferometer for Passive Atmospheric Sounding).

GOMOS has already been described in a companion article in the ESA Bulletin (March 1999). This article focuses on MIPAS (Fig. 2), which is a high-resolution Fourier-Transform spectrometer designed to observe the atmospheric emissions from the Earth's horizon (limb) throughout the mid-infrared region (685 - 2410 cm^{-1}, 14.6 - 4.15 micron). It will be able to make simultaneous measurements of more than 20 atmospheric trace gases, including almost the complete family of nitrogen oxides (i.e.NO_y) and several CFCs (chlorofluorocarbons).

Mission objectives

Stratospheric chemistry

The primary aim of MIPAS is to advance the understanding of the chemistry of the stratosphere, which is essentially the study of stratospheric ozone. Large decreases in stratospheric ozone have been recorded over the Antarctic for many years, but more recently significant reductions in ozone levels have also been observed at northern middle and high latitudes. The main cause of these reductions in ozone levels in the stratosphere is the anthropogenic emission of certain trace species into the atmosphere, in particular the CFCs.

Following the implementation of the Montreal Protocol (an International Treaty to eliminate the use of CFCs), the increase in the average concentrations of these compounds in the troposphere has now slowed down and, as a consequence, chlorine loading in the stratosphere is expected to start to decline

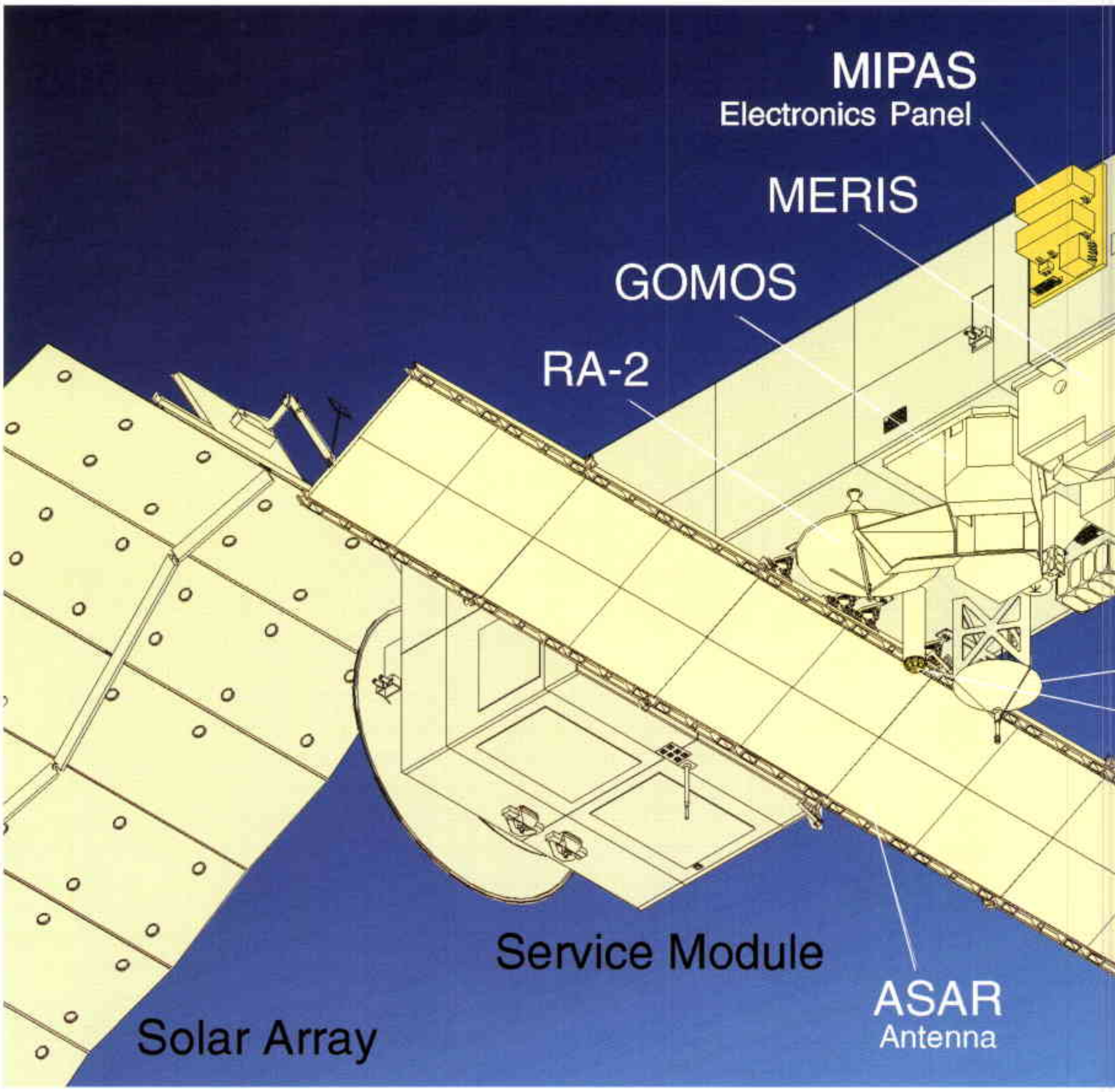


Figure 1. Envisat in flight configuration, highlighting MIPAS and the other atmospheric-chemistry instruments

during the next decade. However, the impact of this on ozone concentrations in the stratosphere in the subsequent years will depend on some chemistry-climate interactions which are not fully understood.

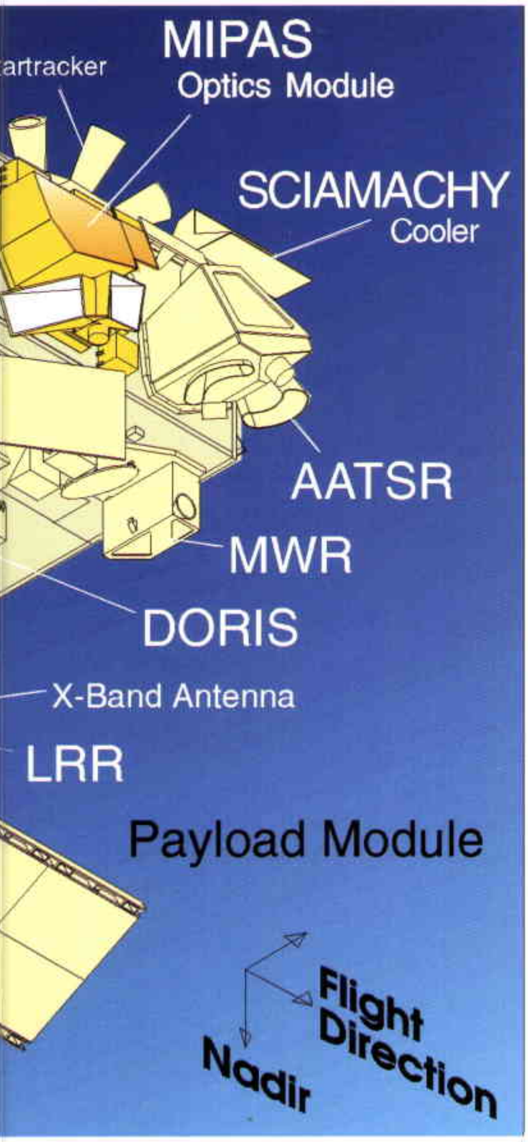
The impact of the increasing greenhouse effect will lead to a continuous cooling of the stratosphere, which could be associated with enhanced polar stratospheric cloud (PSC) formation and a consequent increase in heterogeneous chemical processes in the lower stratosphere. This increase in the greenhouse effect will also modify stratospheric dynamics so that changes in the large-scale distribution of ozone are to be expected. Again these processes are not properly understood.

In order to understand the distribution and levels of ozone in the lower stratosphere, heterogeneous reactions on the surfaces of aerosols and PSCs must also be taken into account. To improve stratospheric photochemical models, simultaneous global measurements of the trace gases that act as sources, sinks and temporary reservoirs of chemically active radicals, as well as of the radicals themselves, are required.

Reflecting these needs, MIPAS has been designed to observe a large number of these trace constituents simultaneously (see Fig. 3), including the whole NO_y trace-gas family (apart from nitrogen trioxide), and several source gases including CFCs. It will be possible to observe changes in the distribution of ozone in time and space over the whole depth of the stratosphere (down to the tropopause) from pole to pole. Furthermore, as an emission sounder, MIPAS will be capable of making observations in the polar night and will observe the polar regions on a regular basis.

Atmospheric dynamics and stratospheric/ tropospheric exchange

The distribution of trace gases in the stratosphere, its thermal structure and its circulation result from a complex interplay between radiative, chemical and dynamical processes. Photochemical theory alone cannot



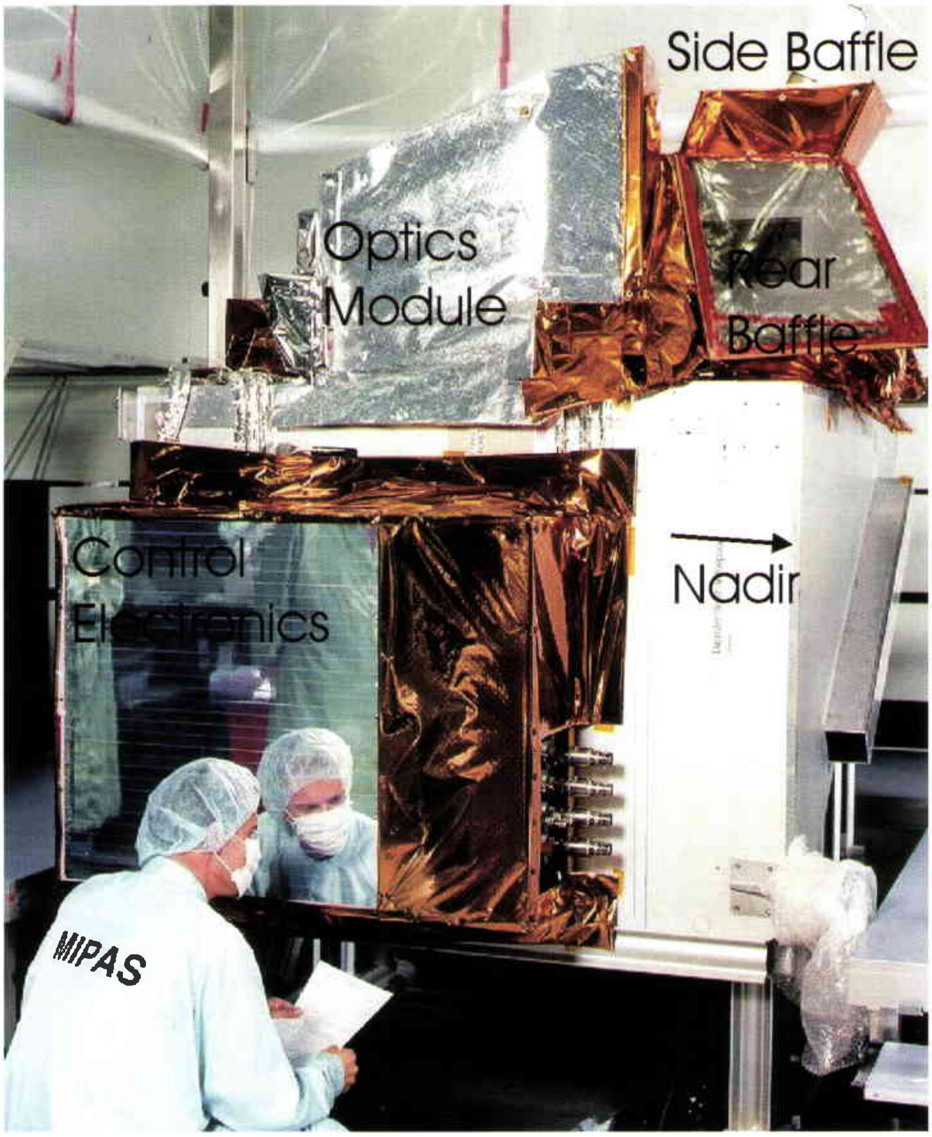


Figure 2. MIPAS instrument during test preparation. In flight, Earth would be to the right

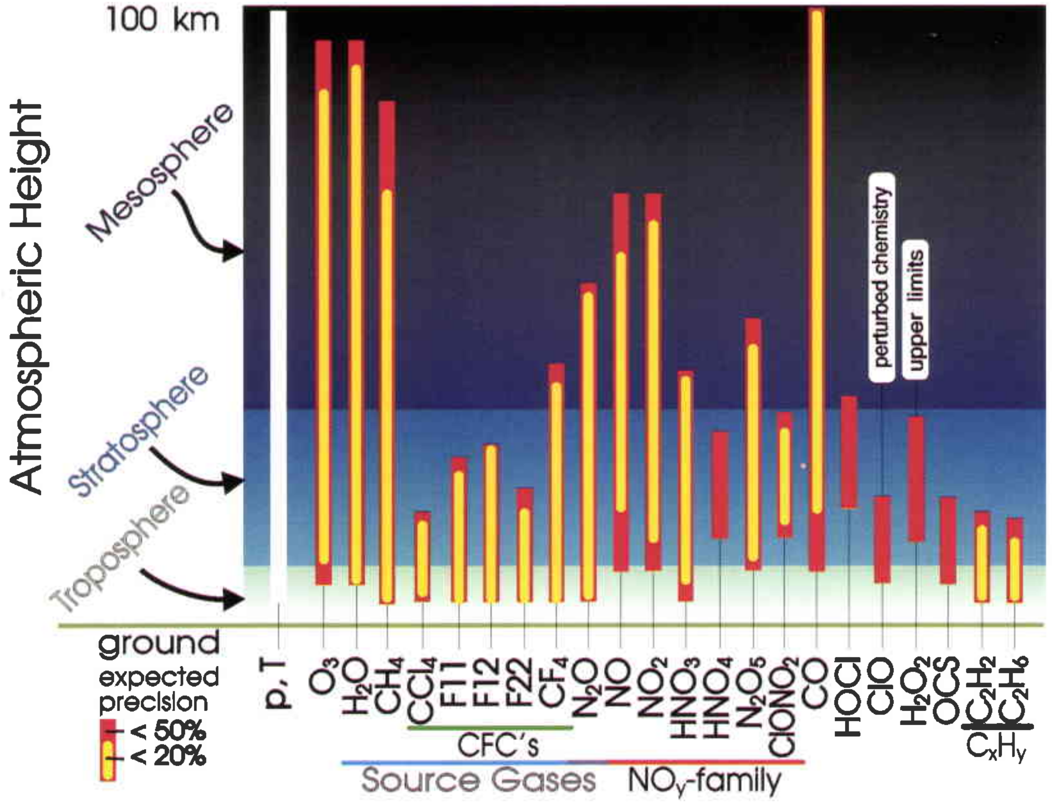


Figure 3. Anticipated altitude ranges and precisions for species that can be detected by MIPAS

explain the distribution of trace species as dynamical processes must be taken into account. Representations of meridional averages of atmospheric circulation have traditionally provided useful insights into both atmospheric dynamics and transport processes.

Here MIPAS has an important role to play as it should be possible to use its observations of temperature, ozone and water vapour in the stratosphere to infer atmospheric circulation arising from atmospheric heating. These can be compared with other MIPAS observations of tracers, providing an opportunity to develop a better understanding of the effects of large-amplitude transient disturbances.

The usefulness of MIPAS data for dynamic investigations will be increased by the provision of a special 'dynamics' limb scanning mode, i.e. making higher spatial density measurements of the vertical profiles of temperature and certain long-lived trace species. This special scan mode will be used to provide either a denser sequence of vertical profiles along-track or additional profiles on both sides of the main track. This will lead to much better horizontal coverage, so permitting the study of medium-scale structures.

An area of major interest in the field of atmospheric dynamics is stratospheric/ tropospheric exchange. Here MIPAS can make notable contributions by providing observations of a number of trace species whose vertical gradients in mixing ratio change rapidly in the vicinity of the tropopause. The deformations of these gradients are indicative of vertical displacements in the air column. By the provision of accurate observations of quasi-conservative trace species of tropospheric origin, MIPAS will allow the processes involved to be studied in some detail.

The chemistry of other regions of the atmosphere

The upper troposphere - this forms part of the lowest layer of the atmosphere, spanning the region between the Earth's surface and the tropopause. It is not readily accessible to limb sounding from space, except in areas in which high clouds are absent. This part of the upper troposphere is characterised by low temperatures, relatively low water vapour concentrations and, being remote from the strong natural and anthropogenic emissions at the Earth's surface, is relatively unpolluted so that chemical reactions proceed at slow rates.

Because the region was perceived as chemically inactive and is not readily accessible to in-situ measurements, the study of its chemical composition and processes has for a long time been neglected. Interest in its chemistry increased dramatically when it was recognised that the emissions of the current fleets of aircraft make a significant contribution to the NO_y budget in this region and had the potential to enhance photochemistry and ozone production in this region.

As Figure 3 indicates, MIPAS should make a major contribution to work in this area by providing information about the major players involved in upper tropospheric chemistry, namely nitric oxide, nitrogen dioxide, ozone and carbon monoxide. It will also provide observations of other parameters important for the study of the chemical composition of the upper troposphere including temperature.

The upper atmosphere - the sensitivity of MIPAS will also allow the observation of many important atmospheric parameters in the mesosphere and lower thermosphere, namely temperature, water vapour, methane, carbon monoxide, carbon dioxide, ozone and nitric oxide. Observations made by MIPAS of these constituents should boost research into three major aspects of the middle atmosphere: temperature structure and energy balance, chemistry, and dynamics.

From the measurements of emissions associated with the presence of carbon dioxide, the hydroxyl radical and nitrous oxide it will be possible to determine total radiative heating and cooling of this region. There is also the long-standing problem of the so-called 'ozone deficit' in the upper stratosphere and lower mesosphere, which has been resurrected recently and which MIPAS data should help to resolve. The observation of carbon monoxide and dioxide will enable the total carbon budget in the upper atmosphere to be determined. The measurements of various tracers, in particular carbon monoxide, will also provide important insights into the dynamics of the mesosphere and the upper part of the polar vortex.

It is important to note that atmospheric fluctuations increase in amplitude with increasing altitude and that it is possible that global changes in climate may act the same way. If so, global change could probably be detected sooner in the upper atmosphere than elsewhere, and so observations of temperature made in this region could prove to be of crucial importance in its detection.

Scientific requirements

Associated with the potential of MIPAS to contribute to many important areas of science is a set of quite stringent scientific requirements.

To meet these, the instrument must be capable of observing over a wide spectral range (i.e. 4.15 to 14.6 micron) to high radiometric and pointing accuracy, as summarised in Table 1. Unless it meets these requirements, it will not be possible to derive the requisite distributions of target species and geophysical variables.

Pointing requirements

MIPAS is designed to observe the radiance emitted by atmospheric constituents tangentially through the Earth's atmosphere, as illustrated in Figure 4. In this 'limb-viewing geometry', the instrument views the radiance from a long atmospheric path, so it is very well suited to detect trace species.

The signal obtained in limb viewing comes mostly from the region around the tangent point, but includes contributions from higher layers. Thus, to determine concentration profiles, the contributions from higher layers must also be measured by taking spectra from higher tangent altitudes. The vertical resolution obtainable from limb measurements is in the order of 2 to 3 km, which is significantly better than that from nadir-viewing instruments.

Table 1. MIPAS performance requirements

Pointing Requirements	
Instantaneous Field-of-View	3 x 30 km^2 (height x width)
elevation pointing	5 ... 210 km above earth limb
azimuth pointing	35° rearwards, 30° sideways
pointing stability (1σ)	0.005° over 4 s
	0.016° over 75 s
pointing knowledge	0.032° after calibration
Spectral Requirements	
spectral range	685 .. 2410 cm^{-1} (14.6 .. 4.15 μm)
spectral resolution	0.035 cm^{-1}
spectral resolution modes	down to 1/10 full spectral resolution
Radiometric Requirements	
radiometric sensitivity NESR	50 ... 4.2 nW/cm^2/sr/cm^{-1}
absolute radiometric accuracy	1% (@14.6 μm) ... 3% (@4.15 μm)
	(relative to input radiance)
Operations Requirements	
max. time per spectrum	4.6 s (full spectral resolution)
	1.0 s (1/10 spectral resolution)
time per elevation scan	75 s (500 km ground trace)
spectra per elevation scan	16 (full spectral resolution)
	75 (1/10 spectral resolution)

Figure 5 indicates the basic observation geometry of MIPAS. The instantaneous field-of-view (IFOV) is only 3 km high (giving a good vertical resolution), but 30 km wide to collect sufficient radiance, corresponding to an angular

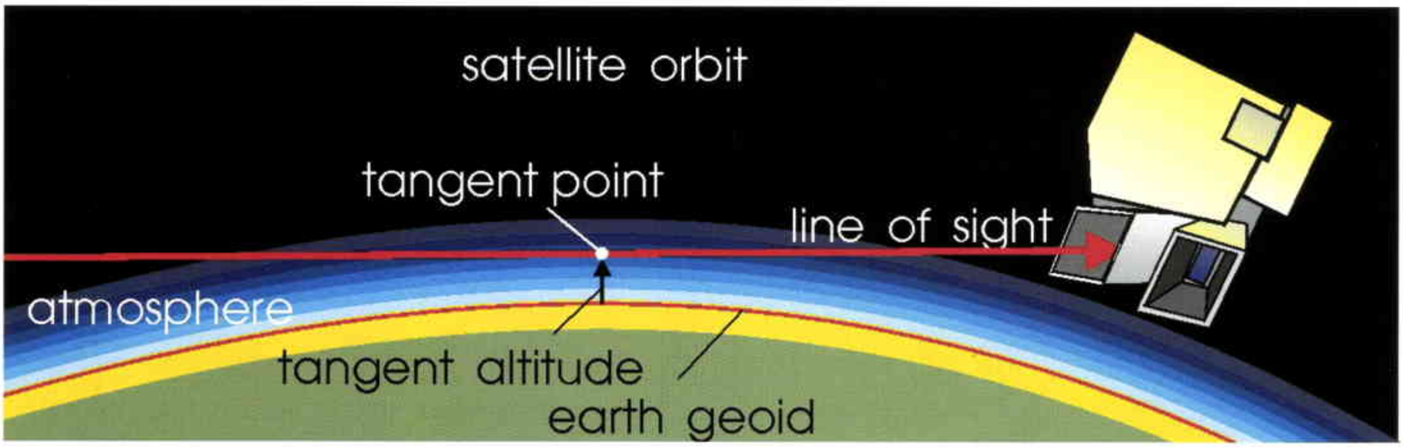


Figure 4. Limb viewing geometry of MIPAS

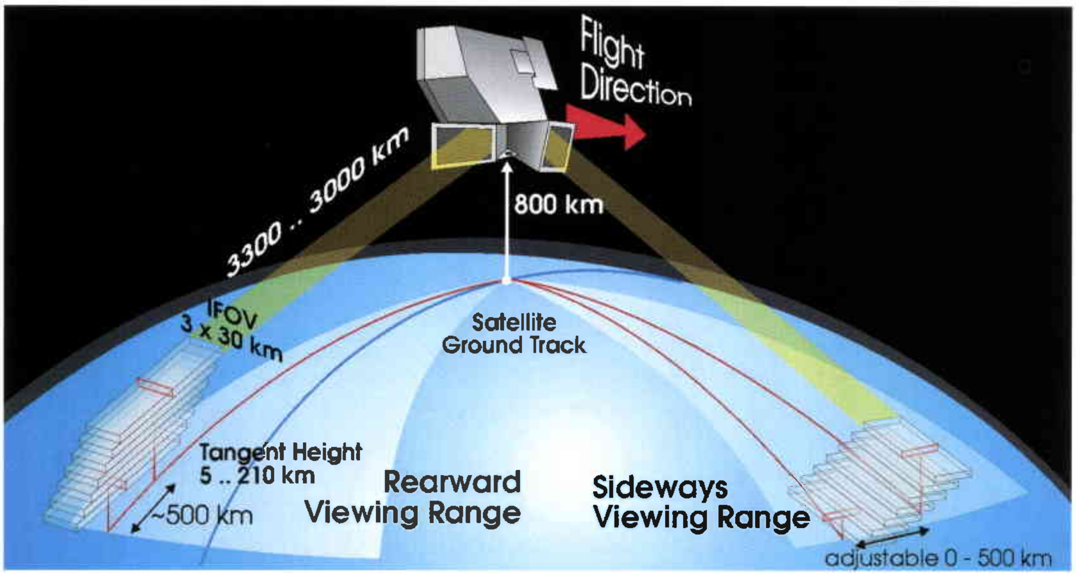


Figure 5. MIPAS observation geometry and rearward and sideways viewing ranges

range at the instrument of 0.05 deg (vertical) by 0.5 deg (horizontal).

MIPAS can observe rearwards (in the anti-flight direction) within a 35 deg wide arc and sideways (in the anti-Sun direction) within a 30 deg wide arc. For routine measurements, MIPAS will focus on the rearward viewing direction as this provides a good global coverage including the polar regions. The sideways range will be important to observe 'special events', like volcano eruptions, trace-gas concentrations above major air-traffic routes, or concentration gradients along the dusk/dawn lines.

As a result of the limb-viewing geometry, the distance between instrument and tangent point is about 3300 km, and so to measure at a predetermined limb height the pointing of instrument and satellite in the elevation direction must be closely controlled. To determine the geometric limb height from pointing information from the spacecraft to better than 900 m, a line-of-sight elevation pointing accuracy of better than 0.015 deg will be required.

The very high stability of all assemblies affecting the pointing is a design driver for MIPAS as well as for the Envisat satellite. To compensate for bias angles (e.g. from launch shifts) and harmonic pointing variations during the orbit, the line-of-sight will be re-calibrated during flight by viewing stars.

Pointing stability during the time that it takes to make a spectrum from one tangent height (4 sec duration) will be much higher – predictions indicate a worst-case height variance of less than 300 m (0.005 deg).

Spectral and radiometric requirements

The spectral coverage encompasses most of the mid-infrared region and contains numerous strong, characteristic emission lines of most atmospheric species. A Fourier-transforming spectrometer is ideally suited to performing measurements over such a wide spectral coverage with high sensitivity.

Figure 6 shows a typical atmospheric radiance spectrum from a tangent altitude of 10 km. The large number of atmospheric emission features in this spectral region is evident. Also indicated are those spectral regions where key atmospheric species have strong emission lines. Concentration profiles of these species can be determined by analysing the effective strength of specific lines from spectra with different tangent altitudes.

To reduce the interference of overlapping spectral features, a high spectral resolution of better than 0.035 cm^{-1} is necessary; this corresponds to a spectral line width of 0.006 nm at a wavelength of 4.15 micron. With this high spectral resolution, MIPAS provides a total of about 60 000 independent spectral samples in each spectrum. A complete high-resolution spectrum is obtained in 4.5 s. MIPAS can also perform measurements with a lower spectral resolution in a shorter time.

Associated with these spectral requirements are some radiometric requirements which are

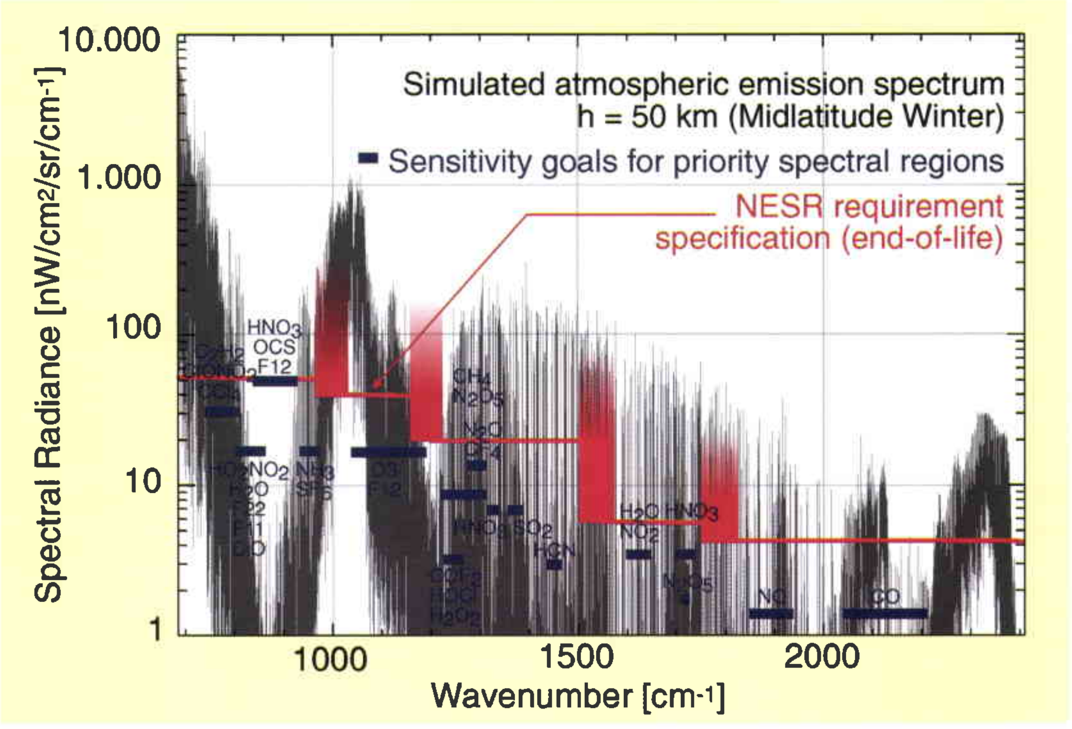


Figure 6. MIPAS sensitivity requirements, expressed in Noise Equivalent Spectral Radiance (NESR), superimposed on the anticipated limb radiance from high altitudes. The red regions indicate the overlap of the MIPAS spectral bands where noise may be higher. Also shown are the NESR-goals for interesting species, assuming single line detection

equally demanding and which are a major design driver. Radiometric sensitivity is expressed here by the Noise Equivalent Spectral Radiance (NESR), which characterises the instrument noise in terms of incident radiance. The required sensitivity is better than 50 nW/cm^2 sr cm^{-1} at the long-wavelength side, decreasing to 4.2 nW/cm^2 sr cm^{-1} at the short-wavelength side.

A good absolute knowledge of the received radiance is important for the retrieval of species concentrations and temperatures. This is quite challenging: a calibration accuracy in the 1 - 3 % range is difficult to achieve even for ground-based instruments. However, the test results of MIPAS indicate that this demanding requirement will also be met.

Design overview

Instrument concept

A Fourier-transform spectrometer (also known as a Michelson interferometer) is the only instrument concept capable of meeting these demanding specifications, as it can be used to observe with a very high spectral resolution over broad spectral ranges using available infrared detectors. However, to achieve the high radiometric sensitivity, all optical components must be cooled to about –70°C to reduce their thermal glow. Although several Fourier-transform spectrometers have been flown in space, MIPAS will be the first one to be cooled.

MIPAS has been developed by Dornier Satellitensysteme in Ottobrunn, Germany (as prime contractor), with the support of 19 subcontractors from 10 European countries. During the development, numerous technical challenges were resolved by this highly motivated industrial team.

The functional block diagram of MIPAS and its ground segment is outlined in Figure 7. Figure 8 shows the schematic layout of the optics module, indicating the optical path of MIPAS from the entrance baffle to the detector elements in the cold unit. The optical layout of the major assemblies is clearly visible in the drawing.

The Front-End Optics (FEO) - The atmospheric radiance enters MIPAS through the front-end optics, which comprises azimuth and elevation scan units for the selection of the line-of-sight, a telescope to shape the light beam and a calibration blackbody for in-flight radiometric calibration.

The entrance aperture of MIPAS accepts an input beam 165 mm in height and 55 mm in width. This free aperture is reduced by Lyot-stops in the interferometer and, before the detectors, to 135 mm by 45 mm for efficient stray-light rejection.

From the entrance aperture in the azimuth scan unit (which is the largest optical component of MIPAS), the beam is reflected to the elevation scan unit, which is designed for very high pointing stability as it determines the tangent height. From there the light enters the telescope, which has different magnifications in azimuth and elevation. It reduces the dimensions of the light beam to 25 mm by 50 mm (in elevation and azimuth, respectively). The telescope also houses the field stop that determines the instrument's field-of-view. The positioning of the field stop in front of the instrument ensures that all detectors view the same air volume.

The Interferometer (INT) - From the telescope, the radiance is directed to the interferometer, which could be considered the 'heart' of the instrument. As shown in Figure 8, the optical path is folded to keep the device more compact. Figure 9 shows the actual hardware. The interferometer is 0.58 m long and 0.36 m wide, and its mass is about 30 kg.

Within the interferometer, the incoming light beam is divided by a beam splitter and the two emanating beams follow different optical paths which are of variable lengths. When the two beams are superimposed again, the light waves interfere and result in a varying output intensity, which depends on the difference between the optical paths. An interferogram is obtained when this interference-modulated signal is recorded as a function of optical path difference. This interferogram is the Fourier transform of the spectrum of the recorded radiation and so the original spectrum can be reconstructed from the recorded interferogram by the inverse Fourier transform.

The achievable spectral resolution depends on the maximum optical path difference. To meet the MIPAS specifications, the optical path difference must be as large as 200 mm. This is achieved by moving two cube-corner reflectors in opposite directions each over a path of 100 mm length. This motion has to be performed with high lateral precision and at a constant velocity throughout the design lifetime of 4 years (corresponding to 20 million motion cycles). To meet this requirement, a design was derived in which the cube-corners are guided by dry-lubricated roller bearings running over stainless-steel rods.

The motion of the cube-corners, as well as sampling of the interferogram, is controlled by a

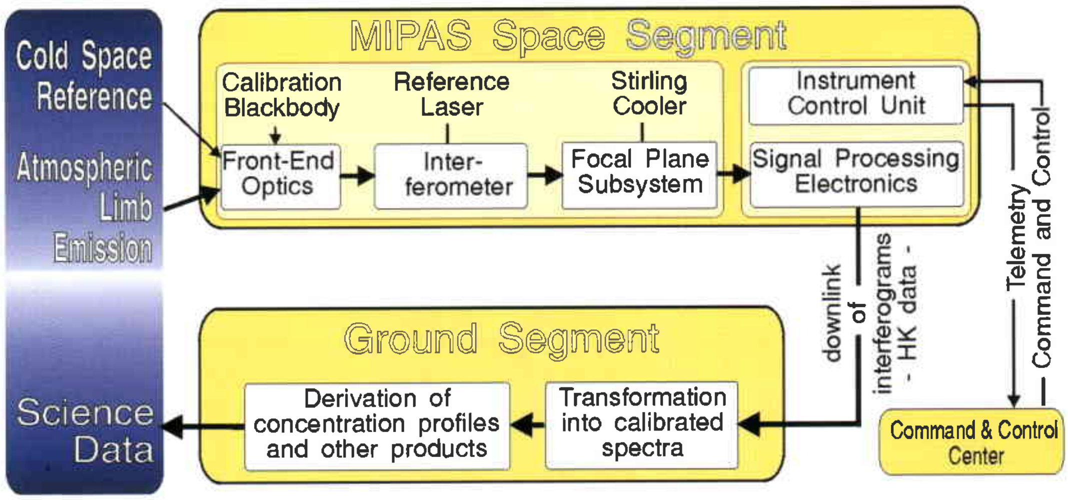


Figure 7. Functional subsystem layout, indicating the major building blocks of the instrument and the ground segment

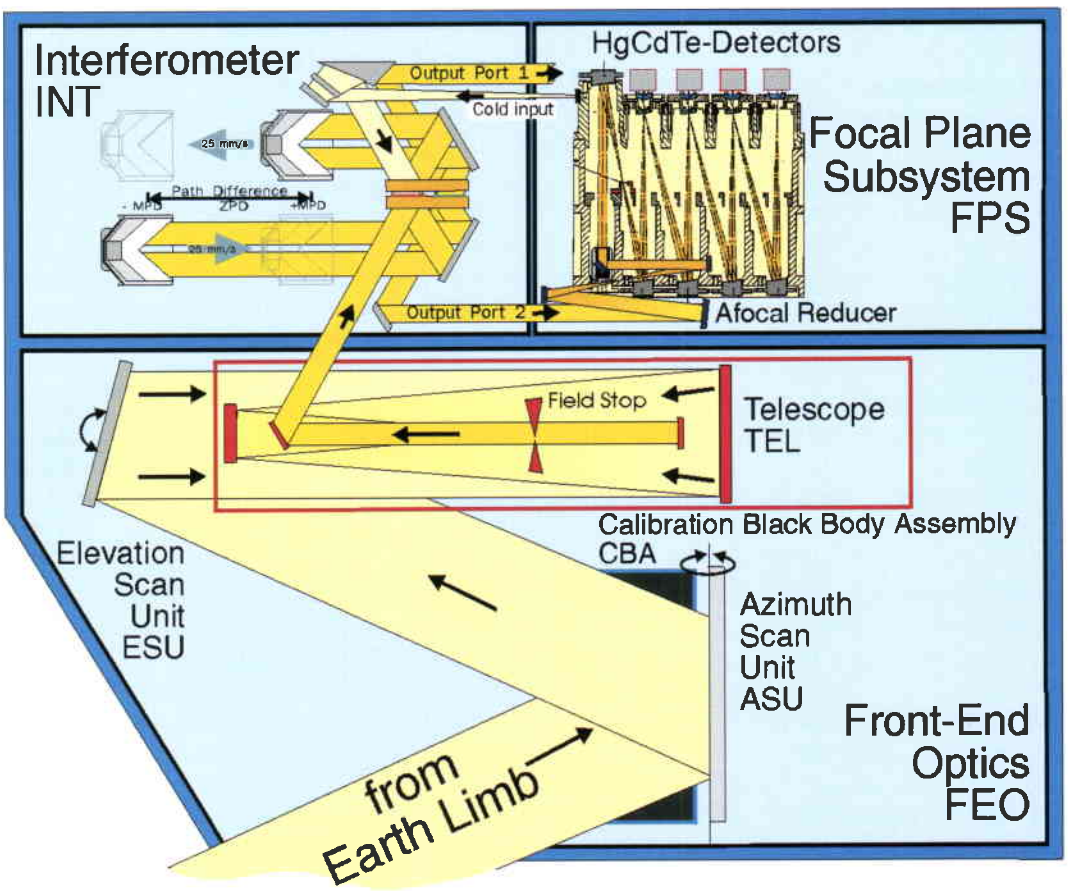


Figure 8. Light path through the MIPAS optics module

built-in laser interferometer. This uses a single-mode 1.3 micron diode-laser as a source, which is temperature-stabilised to limit frequency drifts. The laser package is mounted away from the interferometer to minimise the heat load on the cooled optics. The laser radiation is guided via single-mode polarising optical fibre into the interferometer. Although the individual components have been proven by use in many communication systems, their use in a spaceborne instrument, with operation over a wide temperature range, is new and has required extensive testing to achieve space qualification.

The Focal Plane Subsystem (FPS) - The two output beams from the interferometer are reduced in size by two off-axis Newton telescopes, and directed into the cold focal-plane subsystem. This houses the signal detectors with their interfaces to the active coolers, as well as the associated optics required for spectral separation and beam shaping.

To achieve the best radiometric sensitivity, a set of four Hg:Cd:Te detectors are used in each output port. In the long-wavelength region (7 to 14.6 micron), photo-conductive detectors are used, while the two shorter-wavelength pairs exploit photovoltaic types. They are cooled by a pair of synchronised Stirling-cycle coolers to about –200°C to achieve maximum sensitivity.

The detector-preamplifiers are individually optimised to ensure that each detector meets the stringent requirements on noise, phase distortions and linearity. The cold part of the preamplifiers is mounted in the detector housing, while final amplification is performed in an externally mounted package at room temperature.

The Signal Processing Electronics (SPE) filters, digitises, decimates and formats the output signals of the detectors. The formatted data packages contain the complete interferograms as well as those ancillary data required for the on-ground processing.

The Ground Segment converts the down-linked interferograms into calibrated atmospheric spectra. In the next processing levels, these spectra are used to retrieve the concentration profiles of the relevant atmospheric species and other, higher data products.

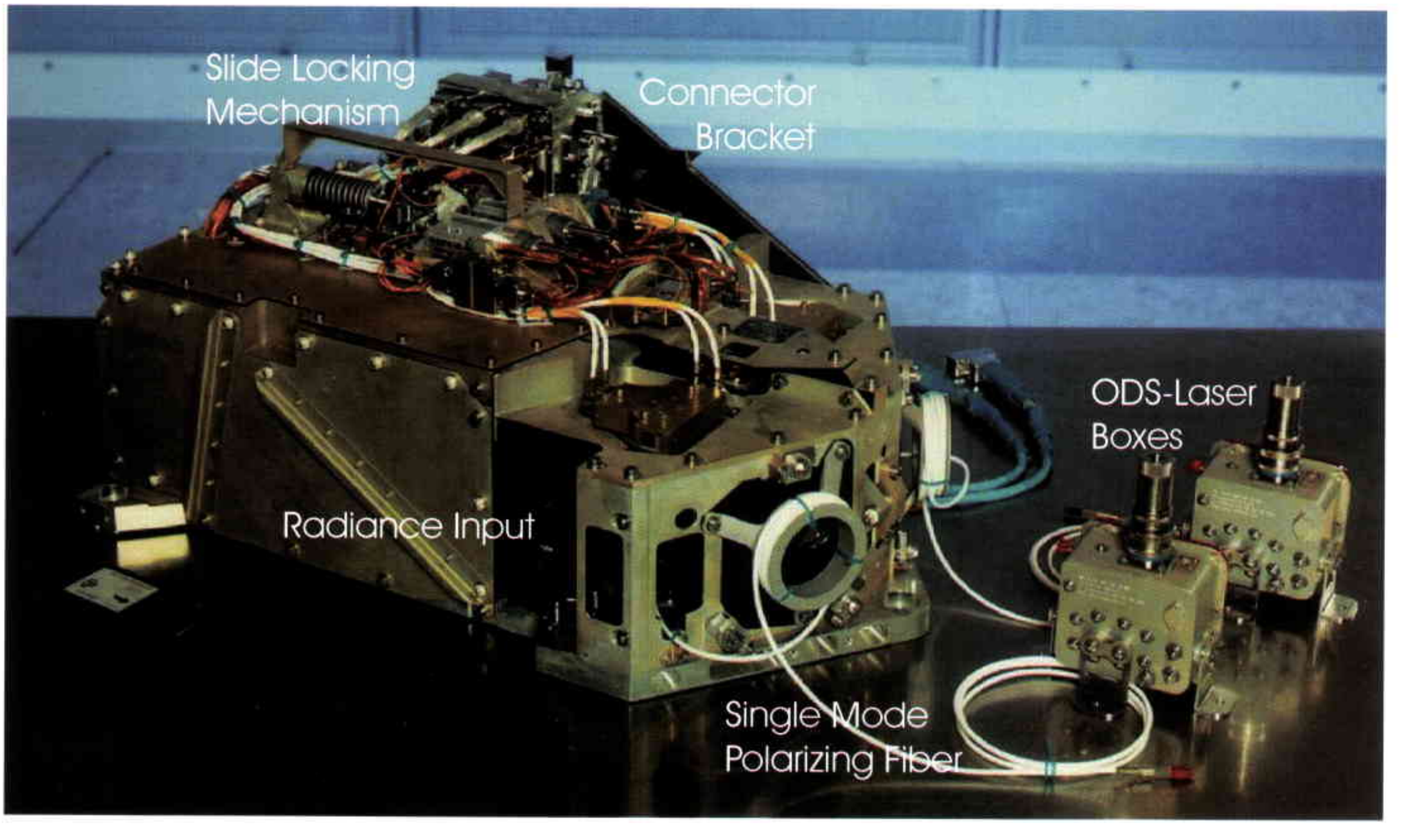
The Instrument Control Electronics (ICE) contains all electronics modules required to supervise and execute macro-commands for MIPAS. It also houses the plug-in modules to drive the subsystems of the interferometer and front-end optics. The Stirling-cycle coolers of the FPS are controlled by a dedicated electronics box.

All of the electronics units are fully redundant: in the case of the instrument control electronics, two identical units are used, while the cooler control electronics is internally redundant. The signal processor electronics uses redundant submodules, which can be switched by telecommand to bypass faulty components.

Accommodation on Envisat

- Figure 10 shows the overall layout of MIPAS as mounted on the tip of Envisat. It comprises the following modules:
- The MIPAS Optics module (MIO) with the azimuth and elevation scan units and the receiving telescope, the interferometer and the focal-plane subsystem, mounted on the tip of Envisat. It is radiatively cooled to about 205 K to reduce the thermal emission of its optical components, but two Stirling-cycle coolers keep the temperature of the detection module to about 70 K.
- The MIPAS Electronics module (MIE) on the side of Envisat, with redundant Instrument Control Electronics boxes (ICE 1 & 2), the MIPAS Power Distribution unit (MPD) mounted on a common carrier plate and under a common radiator for thermal control, and
- Signal Processing Electronics (SPE), Detector Preamplifiers (PAW) and Stirling-cycle cooler drive electronics (FCE) surrounding the Optics Module on the deep-space side of Envisat.

Figure 9. The MIPAS interferometer



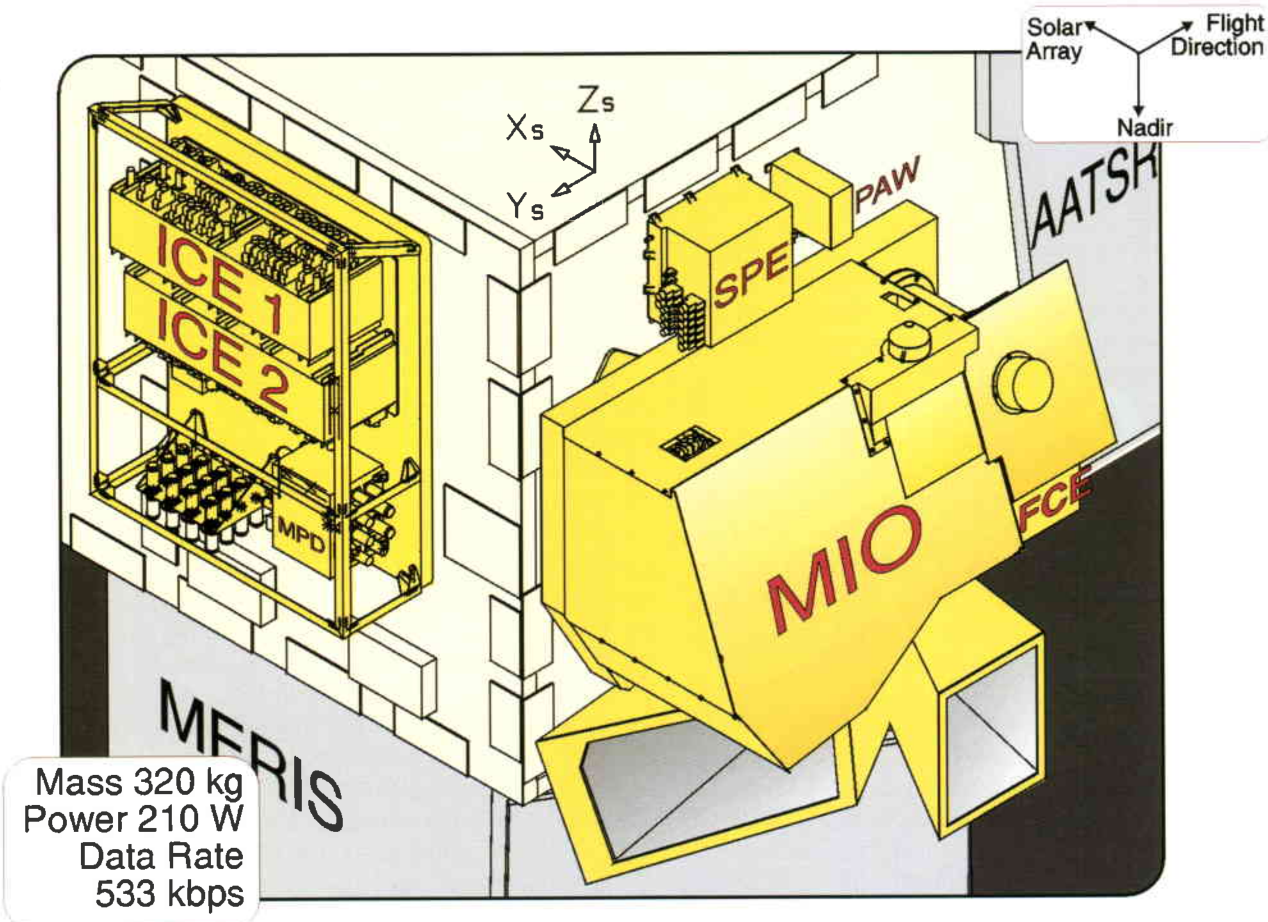


Figure 10. MIPAS mounted on the tip of Envisat

To achieve a lower temperature for the optics, all units with power dissipation are removed from the MIO. However, this distributed concept results in a rather complex instrument harness, as the units in the Optics Module have to be connected to primary and redundant control and monitoring units (it has over 300 connectors).

The total mass of MIPAS is about 327 kg and its power consumption amounts to some 210 W. In elaborate ground tests, it has been demonstrated that MIPAS should perform as specified under the envisaged operating conditions.

The Operation of MIPAS

MIPAS performs measurements continuously. They are either atmospheric observations (i.e. useful atmospheric spectra are derived) or are used for instrument calibrations (subdivided into radiometric calibration and pointing calibration).

Atmospheric measurements

To retrieve concentration profiles, MIPAS obtains a series of spectra at different tangent altitudes, typically starting at about 70 km altitude, and then descending in 5 or 3 km steps down to 7 km. As one spectrum is obtained in about 4.5 s, an elevation scan sequence of 18 spectra takes 80 s. During this time, the spacecraft covers a ground-track distance of about 530 km, but due to the downward scanning the measurement distance increases during the scan, so that the actual spread of tangent points is only 400 km.

The actual elevation scan sequence can be updated in flight to allow an adaptation to the user needs. In addition, time-tagged 'special events' can be commanded with free azimuth and elevation angle ranges, which allow observations of more specific interest, such as pollution along air traffic routes, concentration changes along the dawn/dusk line, concentration profiles near volcanic eruptions, or the support of regional measurement campaigns.

Radiometric calibration

The radiometric calibration of MIPAS is carried out through two types of observation:

- *Offset calibration*, by the observation of cold space to determine the thermal emission of MIPAS
- *Gain calibration*, by the observation of the well-characterised internal calibration blackbody. This also provides information on phase distortions used for the phase correction of the interferograms during ground processing.

Offset calibration has to be performed relatively frequently (several times per orbit) to determine all variations in the instrument's self-emission due to temperature variations. It comprises several low-resolution interferometer sweeps that are co-added by the ground segment to reduce noise and takes only about 20 s.

It is planned to perform gain calibration much less frequently (once per day or less). It comprises a number (about 500) of blackbody - cold space measurements performed at low spectral resolution, which are co-added on the ground to reduce the random noise.

The phase correction of interferograms is very critical for the radiometric calibration. For an emission-sensing interferometer like MIPAS, the best approach is to perform the correction along with the radiometric calibration: the (complex) offset spectrum is subtracted from both the scene spectrum and the calibration blackbody spectrum. These offset-corrected spectra then are divided by each other to derive the proper gain and phase correction. However, this scheme only works if the phase shifts of the interferograms remain constant throughout the time between two blackbody measurements. This requirement of an excellent long-term phase stability is one of the design drivers for the MIPAS instrument.

Pointing calibration
Another set of calibration measurements is performed in-flight to determine the actual Line-of-Sight (LOS) pointing biases and harmonic variations, which in turn set the tangent altitude of a particular measurement. This LOS-calibration is based on the observation of stars moving through the field-of-view with the short-wavelength channels. The actual time of star observation is correlated with the expected time as computed by the pointing information from Envisat's Attitude and Orbit Control System. All the biases and slow pointing variations between the star tracker package of Envisat (providing the pointing reference) and the LOS of MIPAS are derived and used for pointing corrections. The LOS-calibration will be repeated rather infrequently, maybe once per month.

Data processing

Data downlink and processing stages
As outlined in the previous section, MIPAS will perform continuous measurements of atmospheric limb emission, interleaved with periodic radiometric calibration sequences. As a result, a sequence of interferograms and related housekeeping data will be acquired that, with an average data rate of approx. 420 kbit/s, yield a total of 320 Mbytes of raw data collected in each orbit. These data will be recorded on board and downlinked to one of two receiving ground stations typically once per orbit, according to station visibility. The acquisition stations are located in Kiruna (Sweden) and at ESRIN in Frascati (Italy), respectively.

Each downlinked sequence will be converted into a so-called Level 0 product, a computer-readable data set which contains a time-ordered series of data units ('source packets'), together with various header and quality information. The processing of a Level 0 set to higher level products will be performed by the so-called Payload Data Handling Stations (PDHSs) that are co-located with the acquisition stations.

The overall chain comprises two stages, resulting in the so-called Level 1B and Level 2 data products, respectively.

Level 1B component
The first step in the processing chain (Level 0 to Level 1B) covers the conversion of raw scene interferograms into calibrated limb radiance data, making use of pre-processed radiometric offset and gain calibration data, and of spectral axis correction parameters. It encompasses the following primary tasks (Fig. 11):

- *Pre-processing functions* - this includes the extraction and reconstruction of raw scene and calibration data from the Level 0 product, as well as the conversion of instrument housekeeping information (e.g. timing, pointing data) into engineering units
- *Processing of calibration data* - in this step deep-space and blackbody measurements are converted into offset and gain calibration data, which encompasses a number of computational steps such as co-addition (averaging) of interferograms, radiometric accuracy assessment and the validation of processed calibration data
- *Scene data processing and product formatting* - this stage covers the conversion of atmospheric scene interferograms into radiometrically and spectrally calibrated radiance spectra, as well as the computation of different types of annotation data to be included in the Level 1B data product.

A number of functions are common to both calibration and scene data processing, such as correction of detector non-linearity, channel equalisation and combination, detection and correction of spurious spikes in interferogram data and transformations of intermediate data sets between the interferogram and spectral domain by means of Fourier transformations.

Level 2 component
A large number of atmospheric trace gases can in principle be detected within the spectral range covered by MIPAS. However, initially only a set of high-priority target species, O_3, H_2O,

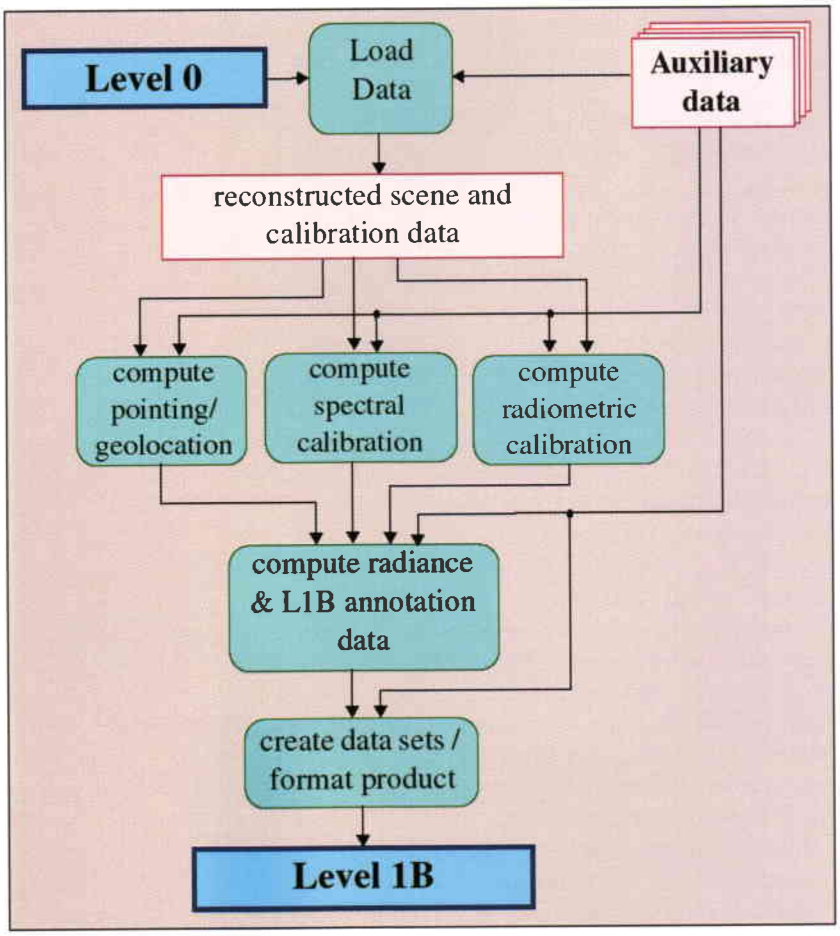


Figure 11. Level 1B processing steps

CH_4, N_2O, HNO_3, have been selected, besides atmospheric pressure (p) and temperature (T) profiles, for routine processing within the MIPAS Level 2 component. All chosen target gases exhibit strong characteristic emission features within the height ranges of interest for MIPAS, allowing the Level 2 analysis to be limited to sets of gas-specific spectral intervals ('microwindows'). In the case of p, T the CO_2 molecule has been selected as a target molecule, providing both a well-known atmospheric mixing ratio and high signal-to-noise ratios in measurable spectral signatures over the full height range of interest.

The retrieval of vertical profiles from sets of limb radiance spectra represents a non-linear problem that cannot be solved in a direct way, and so an iterative procedure has been adopted. This involves the simultaneous analysis of the full set of available observations and minimising the χ^2 function, which is the weighted summation of quadratic differences between observations (radiance spectra at all limb altitudes) and simulated signals (from an adopted atmospheric model). This least-squares fit approach involves the simultaneous adjustment of the unknown quantities (parameters of the model atmosphere).

Product ID	Description	Size
1. Level 1B component		
MIP_NL__0P	MIPAS raw (source packet) data, time ordered. Header and general quality information.	320 MBytes/ orbit
MIP_NL__1P	*Included Data Sets:* Calibrated limb radiance data in the MIPAS spectral bands: A: 685-970 cm^{-1}. AB: 1,020-1,170 cm^{-1}. B: 1,215-1,500 cm^{-1}. C: 1,570-1,750 cm^{-1}. D: 1,820-2,410 cm^{-1} *Annotation data:* Geolocation data, product quality information, processing parameters, noise assessment data, offset calibration data.	330 MBytes/ orbit
MIP_xx1__AX	**Auxiliary products** * Calibration data (gain, offset validation, LOS, ILS) * others (e.g., characterisation data). * orbit state vector/attitude data.	variable size & update rates
2. Level 2 component		
MIP_NL__2P	*Included Data Sets:* Vertical profiles of p, T, O_3, H_2O, CH_4, N_2O, HNO_3. *Annotation data:* Geolocation data, product quality information, processing parameters, others.	5.5 MBytes/ orbit
MIP_xx2__AX	**Auxiliary products** * Pre-tabulated cross-section, microwindows data, atmospheric profiles, pointing information, processing parameters * ECMWF: Meteorology forecast data.	variable size & update rates

Table 2. Summary of MIPAS data products

The functionalities of the Level 2 component can be summarised as follows:

- Extraction of radiance and annotation data from a Level 1B input product and pre-processing of spectra in pre-selected spectral intervals ('microwindows')
- Pressure, temperature profile retrieval, including initialisation of the atmospheric model and least-squares fit analysis of the retrievable parameters
- Sequential retrieval of the volume mixing ratio profiles for the five target species O_3, H_2O, CH_4, N_2O, HNO_3, making use of the pressure, temperature information retrieved in the previous step
- Processing of supplementary parameters ('annotation data') and formatting of the Level 2 data products.

A simplified overview of the Level 2 processing stage is presented in Figure 12.

Instrument Engineering Calibration Facility
The operational Level 1B/2 processors are supported by the so-called Instrument Engineering Calibration Facility, which will perform a number of specific tasks, during both the instrument commissioning and exploitation phases, in particular:

- Monitoring of critical instrument health status parameters
- Validation of radiometric calibration data and optimisation of instrument calibration cycles
- Routine monitoring of specific quality parameters generated by the ground processor
- Characterisation of systematic line-of-sight pointing errors
- Maintenance and regular updating of auxiliary data for use by the Level 1B/2 processing sites.

Data products
The Envisat ground processing concept foresees routine generation, dissemination and archiving of MIPAS Level 0/1B/2 products, as well as the archiving of corresponding auxiliary data sets. This concept will allow users to access to MIPAS data from a few hours after sensing, throughout the full mission lifetime. The information included in the various data products is summarised in Table 2, along with supplementary processing input data ('auxiliary data'), required by the Level 1B and Level 2 algorithm components.

Conclusion
The inclusion of MIPAS on the Envisat satellite represents a unique opportunity to advance knowledge of the stratosphere and stratospheric/tropospheric exchange as well as the upper troposphere and the upper atmosphere. The wide range of species observable, coupled with the ability of MIPAS to observe all parts of the globe, means that significant progress can be made in addressing a number of issues that are of great relevance to mankind.

To realise these mission objectives, MIPAS will have to satisfy a set of very stringent requirements, notably the need to combine high radiometric sensitivity with high radiometric accuracy. Measurements on the flight model indicate that overall performance is within specification, and so MIPAS should indeed meet its specification in flight. MIPAS will be the first cooled Fourier-transform spectrometer to fly in space.

Combining MIPAS data with those from GOMOS and SCIAMACHY represents a unique opportunity for scientists to advance knowledge in some very important areas – a point well reflected in the responses to the recent Envisat Announcement of Opportunity. The synergetic use of the data from these three instruments was anticipated in a very high percentage of the proposals.

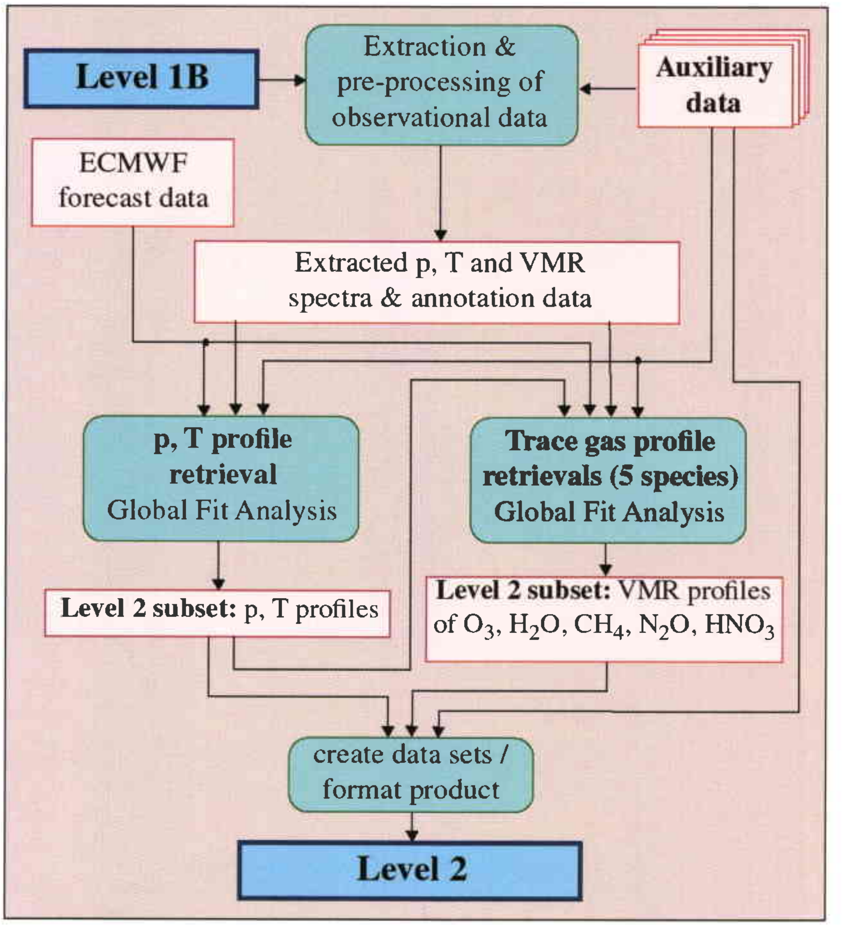


Figure 12. Level 2 processing steps

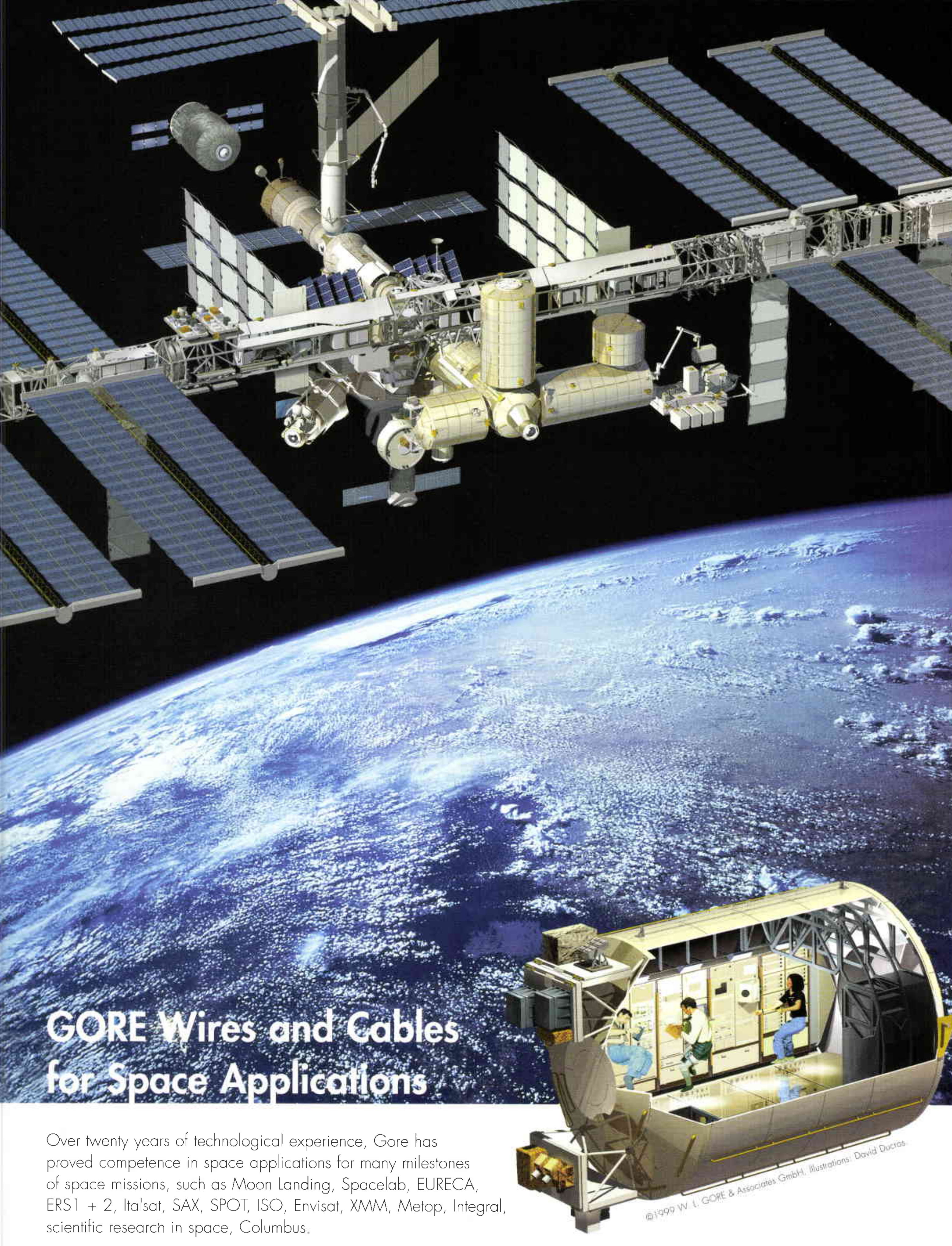

GORE Wires and Cables
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Figure 1. Artist's impression of ERS orbiting the Earth

Figure 2. The O'Higgins station in Antarctica (south of Tierra del Fuego) operated by DLR

The National and Foreign Stations – Key Partners in the ERS Ground Segment

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The Earth Observation Application Department at ESRIN is responsible for the operation of the ERS-1 and ERS-2 ground segment, as well as performing operations for non-ESA Earth-observation missions such as for Spot, Landsat, NOAA, SeaWiFS, etc. The ERS ground segment also includes a component – the national and the foreign stations network – which is not directly operated by ESA, but relies on international agreements for data acquisition, processing and distribution.

The characteristics of the ERS space segment in terms of its multi-sensor payload orbit configurations and power requirements have dictated the geographical implementation of a network of ground stations around the World to acquire the high-bit-rate Synthetic Aperture Radar (SAR) data, for which only direct readout is possible. In addition to the ESA ground stations, a large number of national (belonging to countries participating in the ERS programme) and foreign ground stations (non-participating countries) have been set up or are in the process of being set up around the World in order to acquire, process and distribute ERS SAR data. These stations operate under the terms and conditions of a 'standard agreement' with ESA. This setup allows the extension of the coverage of the SAR operating in Image Mode outside Europe.

In addition to being a vital component of the ERS system, these ground stations expand the market for Earth-observation data throughout the World, showing their strong interest in remote sensing, particularly for the improved management of natural resources. All of the stations concerned are operating in a multi-mission environment, including other SAR and optical missions: the complementarity of sensors and the exploitation of this multi-satellite scenario allows the expansion of applications to different fields and support to operational projects.

The ERS SAR mission and the network of ground stations

ESA, in its Earth Observation Programme, has developed and launched two satellites, ERS-1 (in July 1991) and ERS-2 (in April 1995) carrying advanced radar instruments. Satellites carrying optical sensors rely on sunlight illuminating the Earth in order to obtain useful imagery. Their performances are therefore handicapped by the presence of clouds, fog, smoke or darkness. ERS-1 and ERS-2 do not share those limitations, however, because at their heart is an advanced radar sensor known as Synthetic Aperture Radar (SAR). The SAR is an active microwave instrument that transmits pulsed signals towards the Earth and processes reflected pulses that are received back. Because the ERS-1 and ERS-2 SAR-based technology provides its own 'microwave illumination', it can operate day and night, regardless of the prevailing weather conditions.

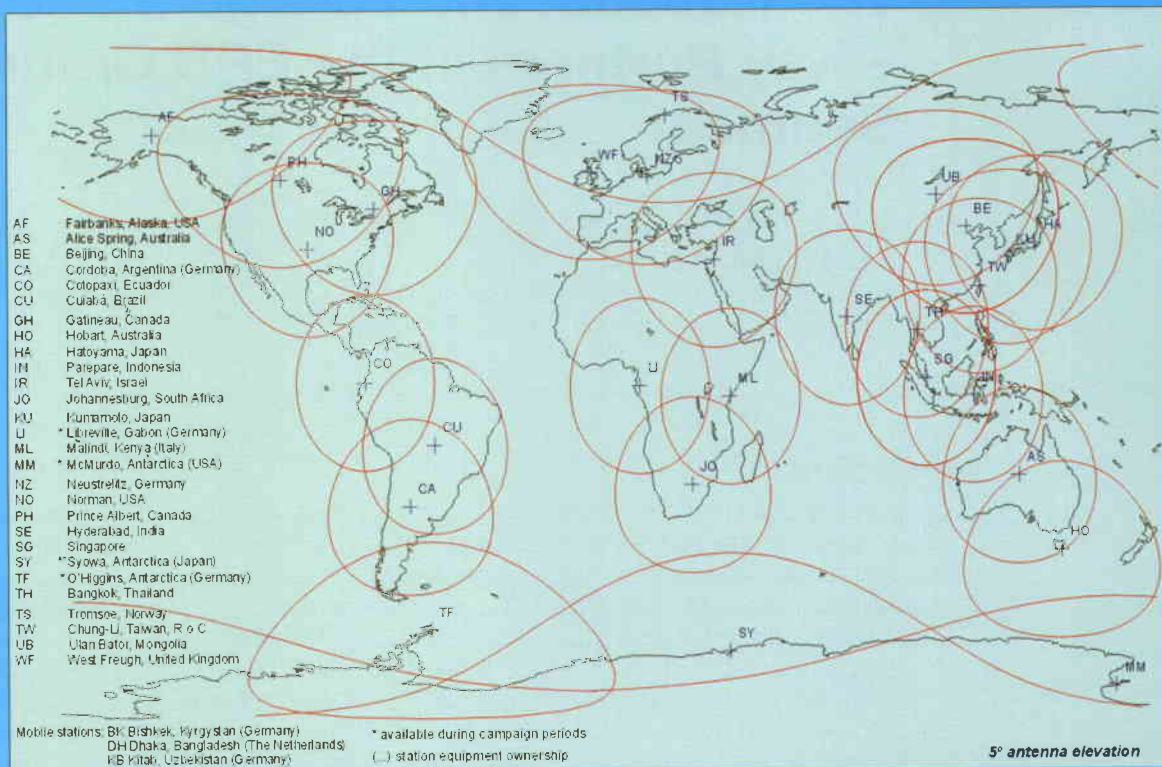


Figure 3. ERS SAR national and foreign station direct X-band link ground coverage

Table 1. National and foreign stations authorised for ERS acquisition

Station location	Ground station operator	Mobile/Fixed	Date of signature (ERS-1)	Date of signature (ERS-2)
National				
Bishkek, Kyrgyzstan	DLR (Germany)	M	19 Oct. 1995	19 Oct. 1995
Dhaka, Bangladesh	NLR (The Netherlands)	M	27 Jan. 1998	27Jan. 1998
Gatineau, Canada	CCRS	F	5 Aug. 1991	10 Aug. 1995
Jakarta, Indonesia	Nri/BURS (UK)	M	11 Mar. 1998	11 Mar. 1998
Kittab, Uzbekistan	DLR (Germany)	M	19 Oct. 1995	19 Oct. 1995
Libreville, Gabon	DLR (Germany)	M	19 Oct. 1995	19 Oct. 1995
Malindi, Kenya	University of Rome (Italy)	F	3 Sept. 1997	3 Sept. 1997
Matera, Italy	ASI/Telespazio	F	N/a	N/a
Neustrelitz, Germany	DLR (Germany)	F	19 Oct. 1995	19 Oct. 1995
O'Higgins, Antarctica	DLR (Germany)	F	19 Oct. 1995	19 Oct. 1995
Prince-Albert, Canada	CCRS	F	5 Aug. 1991	10 Aug. 1995
Tromsø, Norway	NSC	F	19 Jul. 1991	25 Sept. 1995
Ulan-Bator, Mongolia	DLR (Germany)	M	19 Oct. 1995	19 Oct. 1995
West-Freugh, Scotland	BNSC/DERA	F	30 Aug. 1991	25 Sept. 1996
Foreign				
Alice Springs, Australia	ACRES	F	26 Aug. 1991	19 Sept. 1995
Bangkok, Thailand	NRCT	F	22 May 1996	22 May 1996
Beijing, China	CAS/RSGS	F	2 May 1995	17 Nov. 1995
Chung-Li, Taiwan	NCU	F	10 May 1994	25 Aug. 1995
Cordoba, Argentina	CONAE	F	7 Oct. 1997	7 Oct. 1997
Cotopaxi, Ecuador	CLIRSEN	F	29 Nov. 1991	11 Oct. 1996
Cuiaba, Brazil	INPE	F	16 Nov. 1993	12 Apr. 1996
Fairbanks, USA	NASA/ASF	F	14 Jan. 1986	28 Aug. 1995
Hatoyama, Japan	NASDA/RESTEC	F	20 Jun. 1991	1 Apr. 1997
Hobart, Tasmania	ACRES/TERSS	F	26 Aug. 1991	19 Sept. 1995
Hyderabad, India	ISRO/NRSA	F	25 Jun. 1991	6 Oct. 1995
Johannesburg, South-Africa	CSIR	F	10 Mar. 1994	31 Aug. 1995
Kumamoto, Japan	NASDA/TRIC	F	20 Jun. 1991	1 Apr. 1997
Mac-Murdo, Antarctica	NASA/ASF	F	14 Jan. 1986	28 Aug. 1995
Norman, USA	Space Imaging	F	26 Jan. 1995	25 Aug. 1995
Pare-Pare, Indonesia	LAPAN	F	1 Feb. 1995	10 Jun. 1996
Singapore, Singapore	NUS/CRISP	F	3 May 1996	3 May 1996
Syowa, Antarctica	NASDA/NIPR	F	20 Jun. 1991	1 Apr. 1997
Tel-Aviv, Israel	IAI	F	27 Jan. 1997	27 Jan. 1997

The SAR generates a 105 Mbit/s data stream, which is too large to be recorded on board and therefore requires direct transmission to the ground stations. The ERS Instrument Data Handling and Transmission (IDHT) system formats, multiplexes and transmits the payload data via X-band links. It is ESA's goal to ensure global data coverage to the maximum possible extent by cooperating with ground stations distributed around the World which are interested in SAR data applications.

Figure 3 shows the current situation in terms of global coverage, involving a network of more than 30 ground stations. The northeast of Siberia and the Pacific islands are the two land areas not yet covered and ESA is currently in discussion with international partners regarding the use of ground receiving stations enabling that coverage to be provided also.

and via a consortium – Eurimage, Spot Image and Radarsat International – for the other purposes. With the introduction of the revised ERS data policy, the data will be disseminated by distribution entities to be selected in early 2000.

Ground station roles and goals

A ground receiving and processing station usually belongs to a government and is operated by its national space agency or by a remote-sensing organisation, or sometimes by a university.

The main objectives for a ground station are generally to:

- operate the facility efficiently for the purposes of receiving, archiving, and exploiting the Earth-observation satellite data in a commercial fashion

Figure 4. The Cotopaxi station, at an altitude of 3600 m, with the neighbouring volcano in the background

- contribute to international co-operation in the field of Earth-observation applications
- contribute to the country's or region's development by encouraging research and development and applications in the field of Earth-observation science and engineering.

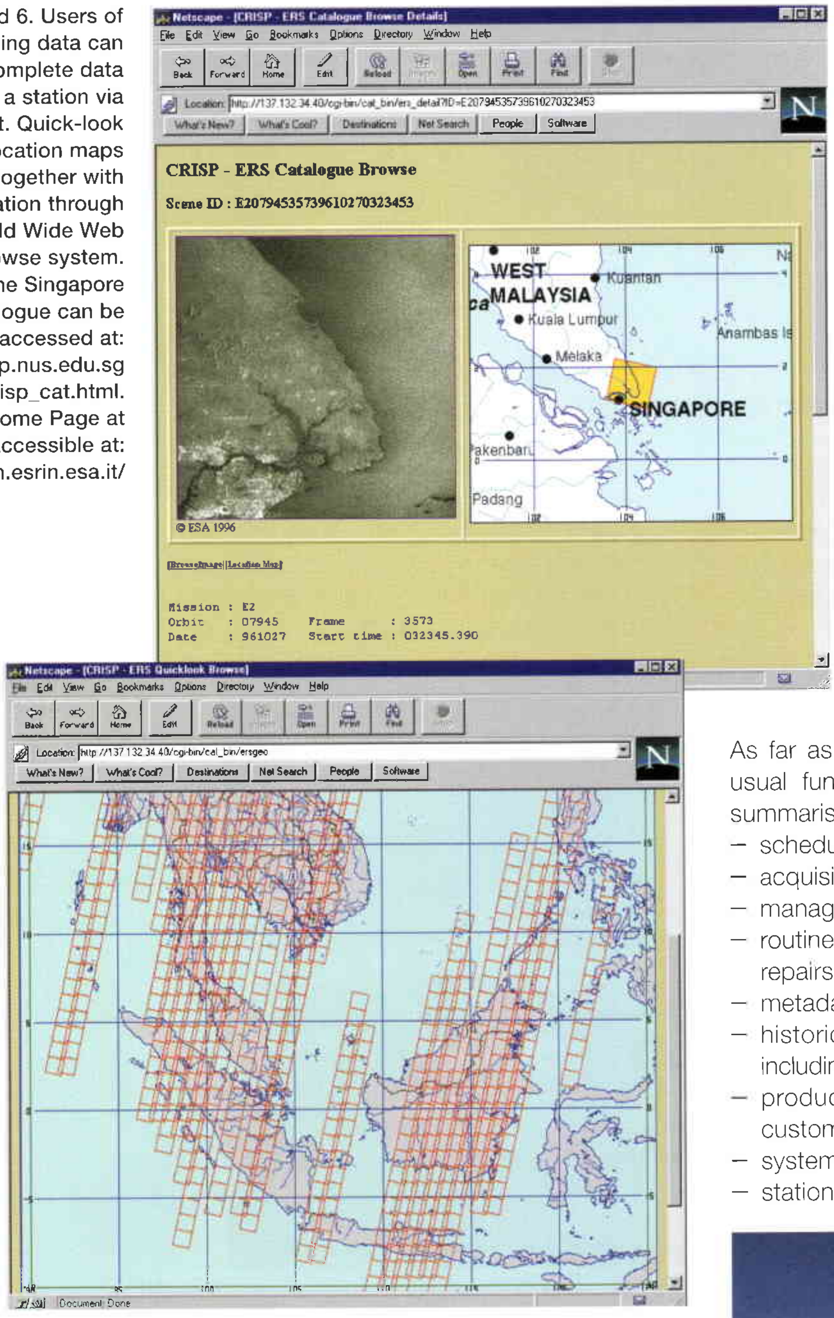
Ground station agreements

ESA and the international organisations concerned have already concluded agreements affording access by the stations listed in Table 1 to the ERS-1/2 missions, as a prerequisite for SAR reception. The ESA data policy dictates that ERS SAR data acquired at any station must be put at the disposal of the user community on a non-discriminatory basis. In particular, for research and demonstration projects approved by the Agency as a result of an Announcement of Opportunity (AO), SAR data are provided free of charge. For other research projects, data are distributed at cost of reproduction. When the data are to be used for operational applications (e.g. agriculture, mapping, etc.), they are charged for on the basis of a price list approved on a yearly basis by the ESA Member States. Today, data distribution is ensured directly by ESA for research, demonstration and promotion usage,

As already mentioned, most of the national and foreign stations support a variety of Earth-observation missions, such as Landsat, Spot, ERS, IRS and Radarsat. The ground stations acquire and process the data received, providing either 'standard' or 'value-added' products for distribution to the users. They can also provide special products on demand, custom processed to users' requirements, and remote-sensing training/consultation services.

The main goal for any ground station is to maintain and periodically refresh a comprehensive archive of satellite remotely

Figures 5 and 6. Users of remote-sensing data can search the complete data catalogue of a station via the Internet. Quick-look images and location maps are provided, together with textual information through the World Wide Web catalogue browse system. For example, the Singapore station's catalogue can be accessed at: http://www.crisp.nus.edu.sg/crisp_cat.html. The Earthnet Home Page at ESRIN is accessible at: http://earth.esrin.esa.it/



The DPF is able to ingest telemetry data in several forms and, through different processing stages, is ultimately able to generate image products on film and other media for distribution to users. The products are normally classified into several levels, depending from the complexity of the processing applied. The station is normally equipped also with browse and metadata generation capabilities accessible via the Internet. In this era of globalisation of information systems, one of the most appreciated features today is the interoperability of the data inventory systems provided by ESA and other international organisations, allowing an easy and common access to local catalogues worldwide.

As far as daily operations are concerned, the usual functions at a ground station can be summarised as:
- scheduling of satellite passes
- acquisition of satellite payload data
- management of local operational tasks
- routine maintenance, troubleshooting and repairs
- metadata and browse-product generation
- historical data-archive management, including long-term data integrity preservation
- product generation and delivery to customers
- system enhancement and upgrading
- station management and administration.

sensed data over their circle of visibility to help and ensure that fundamental information is available for the benefit of the user community. The stations have a range of products and services to suit various data-analysis applications.

Ground-station architecture and operations

A remote-sensing ground station is composed essentially of a Data Acquisition Facility (DAF) used for payload telemetry reception and decommutation, and Data Processing Facility (DPF) that supports the data archiving and product generation. The DAF also performs satellite downlink signal acquisition, including tracking (usually automatic), and supports certain types of testing.

Figure 7. The 11 m antenna on top of the Geophysical Institute's building at the University of Fairbanks, Alaska

Figure 8. A typical early ground-station computer room with, on the right, a High Density Data Recorder and, at the back, the huge racks of array processors and disks. Today, all of this equipment is replaced by that shown in Figure 9

Figure 9. The ESA compact-station Multi-mission Direct Ingestion and Processing System operated by RKA in Moscow

Latest ground-station technology

Technological advances have made ground stations much more affordable nowadays. The availability of greatly increased computer powers and input/output (I/O) speeds has allowed the previous customised/specialised equipment (e.g. recorders, array processors, etc.) to be replaced with standard and commercially available off-the-shelf computer-based architectures. The availability of very fast peripherals with large storage capacities has also increased the overall performances of the ground systems, leading to dramatic reductions in the overall costs. This change in technology has also had a substantial impact on the architecture of the ground segment, allowing also a multi-mission approach with the use of common platforms and common software for handling several missions in parallel.

The simplification of the entire station architecture with the adoption of standard computer interfaces has also increased the availability of off-the-shelf data-processing software, eliminating the need for expensive and customised systems to process data from the Earth-observation satellites.

Advances in technology have also improved the payload data acquisition area, in that smaller (less than 4 m diameter) and cheaper antennas can now provide reliable performances under most operational conditions. The availability of programmable receivers, capable of handling several missions within the same unit, has also reduced the cost and size of the entire station. The improved manageability of the entire system also allows it to be used as a mobile/transportable ground station, adding an enormous degree of flexibility for the overall satellite ground segment. Acquisition campaigns conducted in remote areas have greatly increased the exploitation of SAR data, particularly when ERS-1 and ERS-2 have been operated in tandem (e.g. generation of digital elevation models in areas never previously remotely sensed).

For the last decade, operational processing of raw SAR data has involved rather long processing times and has also required the expertise of experienced radar engineers to understand and interpret data anomalies. Today many companies are offering complete ground processing systems for spaceborne SAR data which are fast and easy to use, including an acceptable and operational product quality-control system.

For the first time, end-to-end systems are available that can capture raw data and process it through the various stages from basic imagery to map quality, i.e. GIS-compatible data products. These rather inexpensive workstation-based processing systems do not require the user to be aware of the details of the SAR sensor being used or the SAR processing algorithms.

Evolution in ground-station architecture

The availability of several high-resolution sensors, the entry into operation of satellite constellations, the growing interest in commercial satellites, and the increasing importance of value-added processing capabilities are all expected to stimulate the evolution in future ground-station architecture. The high cost of procuring and operating the traditional remote-sensing ground station has too often put this capability beyond the reach of all but a handful of national remote-sensing centres around the World. To address this restrictive gap in the market, many companies are introducing new concepts in designing

Figure 10. A RAPIDS mobile station (dish antenna and hydraulic control system) deployed on the roof of SPARSSO agency in Bangladesh

even smaller and more flexible remote-sensing ground stations, increasing their mobility and transportability without impacting negatively on performance and cost.

In order to achieve the high degree of flexibility and expandability required to meet special needs (e.g. disaster warning or data-acquisition campaigns in remote areas), traditional design assumptions regarding equipment, systems, configuration and infrastructure are being completely reassessed. The result will be a new generation of compact ground stations that are easy to transport and to integrate, and can be very quickly put at the disposal of concerned users to provide real-time data and information in crisis situations.

The trend will probably be towards single-sourcing of already assembled and tested ground station systems, with evident benefits in terms of quicker and cheaper procurement and reduced operating costs due to the high level of automation and commonality between different missions.

ESA's role in the worldwide ground-segment scenario

Drawing on the long experience of its Earth Observation Applications Department at ESRIN in designing and operating multi-mission ground segments over some 20 years, ESA has made a remarkable contribution in setting up such a large ERS ground-station network. From the time of ERS-1's launch in 1991, data availability from non-European coverage areas was recognised as critical, given that there was no SAR data recorder on-board and no ad hoc resources were at the disposal of the project. Great were therefore made to find workable solutions for ensuring data availability, data quality and data provision continuity from other international stations, focusing initially on those most critical in terms of their geographical locations and available-resource limitations.

The solutions proposed and implemented covered a wide spectrum of alternatives, including the provision on site of ESA standard recorders, the procurement of specialised equipment for data conversion and transcription (ESA compact station), technical support to the local engineers, and the adaptation and enhancement of existing operating procedures. The advances in technology finally helped by facilitating the installation of compact multi-mission systems able to acquire and directly generate products for users.

Those efforts by the Agency have succeeded in several notable achievements:
- increased collaboration between ESA and the international partners in the remote-sensing field
- enhanced availability of ERS SAR data worldwide
- enhanced exploitation of SAR data in countries traditionally oriented to using optical data
- increased application of SAR data in operational projects, sometimes funded by international organisations
- promotion of European technology in areas previously monopolised by non-European industry
- contribution to the promotion of modern technology in the less developed countries
- increased satisfaction on the part of European users requiring data from remote areas.

Conclusion

To date, more than 30 international ground stations have been erected – some with ESA support – around the World, strengthening the worldwide presence of ERS and providing the foundation for local and regional applications. In addition to being a vital component of the ERS system, these ground stations serve to expand the global market for Earth-observation data, not least for the improved management of natural resources.

ESRIN is a key player and international partner in these global efforts. Future ESA remote-sensing programmes such as Envisat are benefitting greatly from all of the experience gained with the ERS missions, and not least from the impressive ground infrastructure that has been set up in cooperation with all of the other international ground-station operators. This will provide partnership opportunities for commercial Earth-observation initiatives.

A Review of the Long-Term Options for Space Exploration and Utilisation

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ESA's Long-Term Space Policy Committee (LSPC) has underlined the need for Europe to think ahead and establish a vision for its future space activities with a 30-year horizon. The goal is to identify promising opportunities, and to establish in Europe the key capabilities and critical technologies required for the exploration and utilisation of space over the next three decades. Studies and discussions have focused on the Earth-Moon system, Mars, near-Earth asteroids and comets. Scientific motivations are an important aspect in all potential space exploration and utilisation activities, but economic, commercial and technological issues are paramount in addressing central questions such as the preparatory efforts required and the potential benefits.

Introduction

In its second report *'Investing in Space - The Challenge for Europe'*, presented to the Ministerial Council in Brussels in May 1999, ESA's Long-Term Space Policy Committee (LSPC) has identified a number of potential scenarios for developments in space over the next 30 years. These include the expansion of the human presence beyond Low Earth Orbit (LEO), and the utilisation of resources from space on an ever-increasing scale. The scientific exploration of space is an underlying recurring theme.

On the basis of the LSPC's vision, a practical goal for ESA has become the identification of the most promising opportunities in space exploration and utilisation, and the establishment of requirements for implementing the required key capabilities and critical technologies in Europe. To a similar end, ESA had already organised a 'Workshop on Space Exploration and Resources Exploitation (EXPLOSPACE)' in 1998. In the meantime, a study titled 'System Concepts, Architectures and Technologies for Space Exploration and Utilisation' has been carried out on the Agency's behalf by a European consortium, led by the German Aerospace Centre (DLR). The findings of both the Workshop and the study are highlighted in what follows.

Space Exploration and Utilisation (SE&U) scenarios

A large variety of viable applications can be identified within a coherent space exploration and utilisation effort. Applications considered of higher priority have been examined in a structured decision process that has allowed them to be ranked in relative terms, on the basis of their credibility/feasibility, benefit/justification, affordability, and derived benefits for other applications. Combining the most promising applications has resulted in the establishment of four SE&U reference scenarios (Fig. 1). These scenarios have subsequently been analysed in detail and a technology roadmap developed, paying particular attention to long-term strategic technology development. Since long-term scenarios are by nature very uncertain, the approach must be to invest in capabilities and technologies that have enabling potential for multiple applications.

Mars exploration

Scientific interest in Europe in planetary exploration involves several targets. The innermost planets, Mercury and Venus, typically present very challenging mission scenarios, due to their extremely demanding environmental conditions. Innovative technologies would be needed to enable Europe to undertake autonomous exploration missions to these planetary bodies. A different picture is provided by the Moon and Mars, which offer the potential of long-term evolution toward scenarios involving a human presence and in-situ resource utilisation (ISRU). Consequently, both of them figure prominently in any long-term analysis.

The attractiveness of Mars as a target for space missions has increased dramatically with the recent scientific discoveries about the planet, with considerable public interest also being raised. Currently planned missions involving almost a dozen American, European and

Figure 1. Robotic and human Space Exploration and Utilisation (SE&U) scenarios

Japanese probes will lead to a significant expansion of our knowledge about Mars within the next 10 years. These missions include orbiters, landers, rovers, sample-return vehicles and ISRU experiments. Human exploration of Mars, which is a complex and costly endeavour and which may not start much before 2020, will certainly require lengthy preparations and a phased approach, involving sequential milestones or 'plateaus of achievement'.

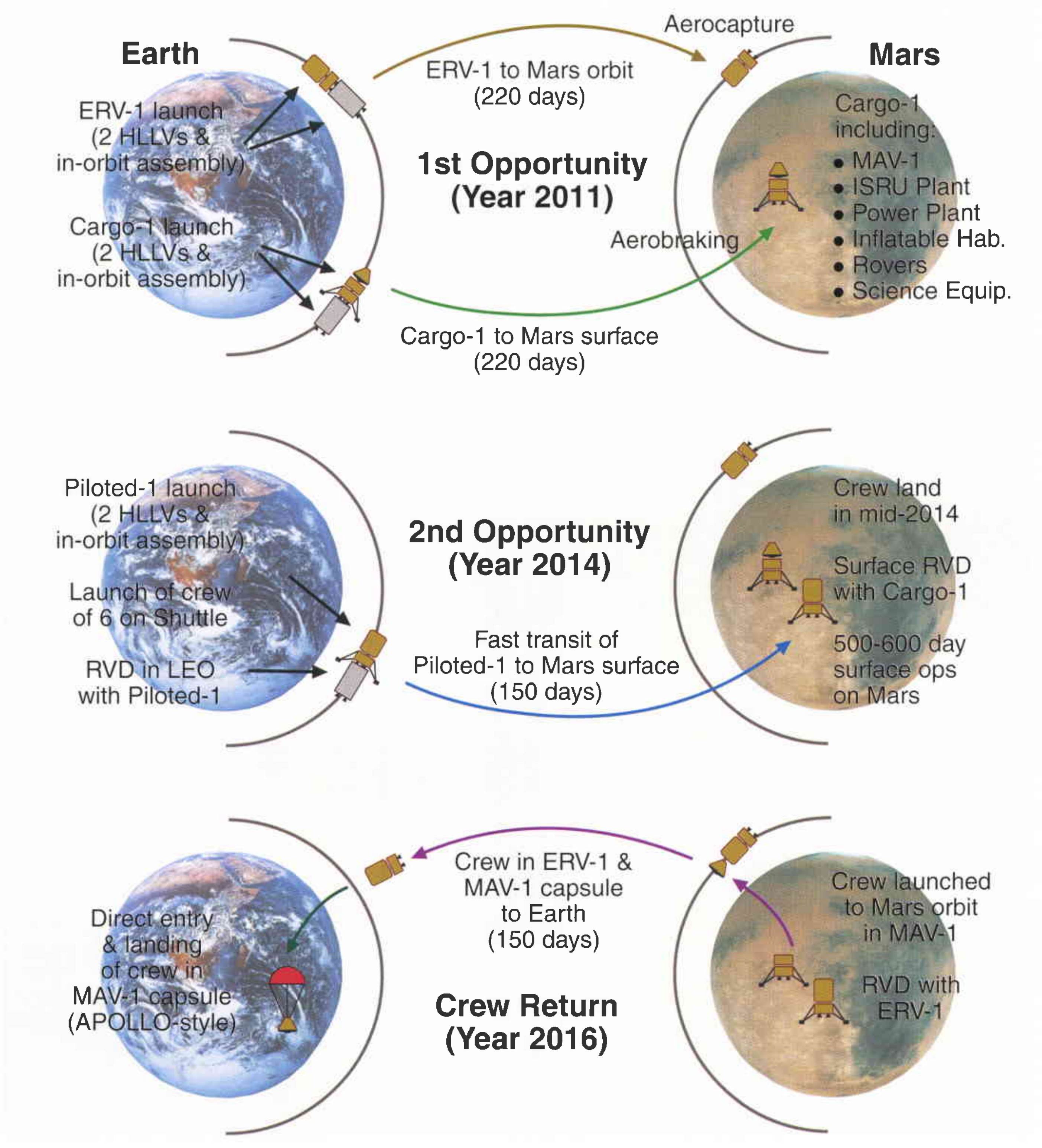
One such plateau would be the establishment of a permanent robotic presence on Mars, based on self-sustainable, expandable colonies/outposts of robots working in networks. These robotic outposts may become critically linked to the human exploration effort, representing the seamless evolution from robotic Mars exploration missions, which are currently approved or in various stages of planning, to human Mars exploration in the longer term. Robots can greatly amplify and replace narrow facets of human capabilities in hazardous and extreme environments, and could be sent to Mars in both pioneering and supporting roles. The robotic outposts would provide multi-dimensional (surface, sub-surface, airborne, and orbital) coverage capabilities over wide areas of the Martian surface. They could carry out long-term network science (e.g. seismology, meteorology) and multi-site science (e.g. geology, mineralogy) operations. Deep subsurface exploration could be conducted, with the aim of assessing water resources in underground reservoirs, at depths ranging from a few tens to a few hundreds of metres.

The robotic outposts would exploit a robust infrastructure of standardised high-bandwidth communications, high-capacity computing and data storage, power, navigation, surveillance and weather stations on the surface, in the atmosphere, or in Mars orbit. Data rates in the order of Mbit/s would be achieved by means of a mini-/microsatellite relay network. Systems for robotic outposts may feature a high degree of autonomy and co-operative behaviour, under the control of 'remote agents' and high-level human supervision. Extended lifetimes, in the order of decades, could be achieved by employing expandable, upgradable, replaceable systems capable of mutual/self repair and/or pre-planned functional improvement via the exchange of modules.

The resources needed to commence the human exploration of Mars may become available towards the end of the build-up phase of the International Space Station (ISS) around 2005. NASA's Reference Mission scenario, representing its latest approach to a human Mars exploration endeavour, features a split mission concept (Fig. 2) in which three human missions, each including a crew of six and involving two robotic cargo flights, would be launched over a period of about 10 years. The proposed Trans Mars Injection (TMI) stages feature nuclear propulsion systems. Reduced launch costs are assumed to be achievable by the development of the Magnum heavy-lift launcher (with a payload capacity of 75 t to LEO), based on post-Shuttle technology.

Variations of this scenario were analysed in the ESA-sponsored SE&U study to gather detailed information about the costs, masses and technologies involved. Options considered included: nuclear thermal, chemical, and solar electrical TMI stages, with or without ISRU plants on Mars or on Phobos. The main results of these analyses indicate that the lowest masses at LEO departure would be achievable with TMI stages based on solar electric propulsion. A life-cycle cost reduction of several billion dollars may be possible in various sub-scenarios, with respect to the $ 42 billion calculated for the first human mission in NASA's Reference Mission scenario. The use of nuclear propulsion as proposed by NASA appears to be problematic, for both technical and political reasons. Although the solar-electric design has the strongest potential for mass and cost savings, it also requires the greatest development

Figure 2. NASA's reference concept for the first human Mars mission



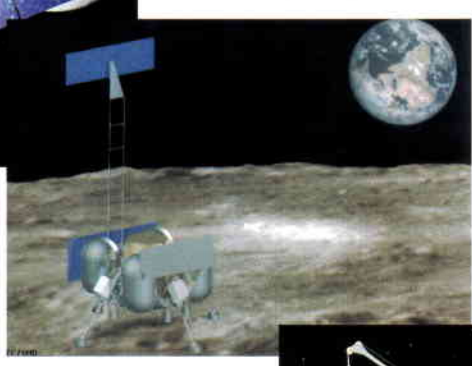
effort in terms of new technologies. Presently, a sub-scenario with chemical TMI stages and propellant production on Mars appears to be the most promising option, and is being recommended as a new baseline mission. An otherwise appealing scenario involving a single-stage spacecraft, which is re-fuelled on Mars and Phobos, is rendered rather hypothetical by the lack of direct evidence for accessible water on Phobos.

Despite these and other uncertainties still affecting human Mars mission concepts, estimates of the total programme costs for three human missions of about $52 billion correspond to relatively modest annual costs of $2.6 billion for a 20-year programme. This is roughly equivalent to the current annual budget for Space Shuttle operations. It therefore appears that robotic preparatory missions can indeed lead to an affordable mission scenario that could result in the first human landing on Mars fifty years after Apollo.

Moon exploration
'Science of the Moon', addressing the origin and evolution of the Earth-Moon system and 'Science on/from the Moon', involving a large variety of experiments and observations on/from the lunar surface, have long superseded national prestige as the main drivers for lunar exploration. This SE&U scenario also provides numerous opportunities and challenges as a technological test-bed, especially in the context of future human missions to Mars. Today's knowledge about lunar materials and the potential presence of water ice in the polar regions have resulted in increased interest in ISRU applications.

A stepwise approach towards renewed lunar exploration, as proposed in the Resolution resulting from the 1994 International Lunar Workshop in Beatenberg, Switzerland, involves as a first step the robotic exploration of the Moon, aimed at filling significant gaps in our existing knowledge. This goal may be achieved within the first decade of the new millennium and would require orbiters, landers and rovers with ranges of several tens to hundreds of kilometres. European missions such as SMART-1 can also play a crucial role in this phase, even at a reduced level of funding. Subsequent steps, reaching their peak of activity after 2010, would involve more sophisticated and diverse systems, such as automated observatories, autonomous rovers and sample-return devices, as well as pilot plants for oxygen, power, fuel and eventually food and construction-material production.

If during these exploratory missions it becomes obvious that a human presence on the Moon is mandatory for scientific and/or other reasons, a series of human missions can be envisaged to resume around 2020, thereby establishing an initial lunar outpost that may ultimately evolve into a permanent lunar base. This phase would require an increase in crew sizes from 2 to perhaps 8, and gradually increasing stay times on the Moon. Such a human mission scenario depends strongly on greater international co-operation, efficient and innovative use of lunar resources (mainly lunar oxygen bound in silicates and oxides) and the



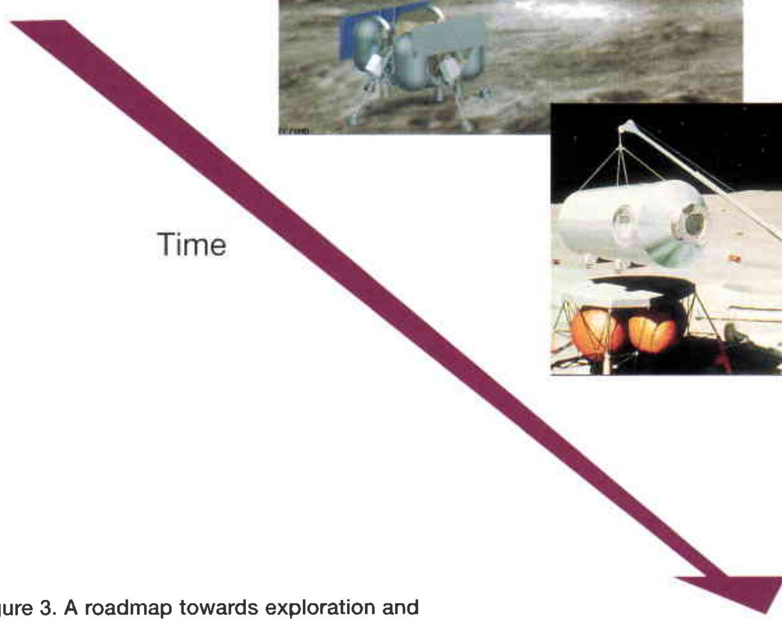


Figure 3. A roadmap towards exploration and utilisation of the Moon

development of adequate transportation vehicles (Fig. 3).

Assuming a 10-year development period, the projected costs for building and operating a growing human lunar infrastructure for say 9 years are about $85 billion. An alternative and more optimistic estimate with respect to advances in cost-saving technologies, such as the availability of a cheap reusable transportation infrastructure, results in costs of about $57 billion. Extensive in-situ resource utilisation has the potential to produce additional savings of at least 10%.

Overall, therefore, an increased European effort in lunar exploration appears to promise valuable technological and scientific returns at moderate costs at least during the robotic phases. With the efficient use of cost-saving strategies, a human return to the Moon also appears to be affordable and may be realised prior to the first human landing on Mars, if the public can be convinced of its value.

Near-Earth Objects

Minor bodies (asteroids and comets) which periodically come into the Earth's vicinity are also potential targets for future space applications, both because of their scientific value and the potential threat of catastrophic collision that they pose for Earth. The geological record of the Earth shows a considerable number of impacts of such bodies on its surface.

A short-term 'local' threat is posed by a large population of small potential impactors in the 10 – 100 m size class, which is poorly known and which may arrive at short notice due to their late detection. A more 'global' threat is posed by the larger kilometre-sized bodies, on a longer time scale. Current efforts are aimed at characterising the Near-Earth Object (NEO) population accurately, and establishing a catalogue, by conducting ground-based surveys (the approach of the Spaceguard Foundation). At the same time, in-situ investigations of the material composition (ice, rock, metals) and structure of NEOs should be conducted, to provide ground truth for multispectral remote sensing from Earth. This fundamental information will form the basis for a hazard assessment, and for eventual threat-mitigation strategies. Emphasis is not being placed on mitigation measures until the actual risk can be determined more clearly by the scientific community.

The determination and prediction of NEO orbits is rendered difficult by the chaotic elements involved, and therefore the results of a deliberate action aimed at deflecting such an object are highly uncertain. Mining of NEOs for precious metals and semiconductor materials will probably become feasible in the 21st Century, although it is currently unclear if it will also become economically profitable compared with terrestrial alternatives, such as the mining of ocean floors.

Space Solar Power

The World's growing energy demands and the environmental and safety problems associated with conventional power plants warrant the consideration of solar energy as a major power source for the future. The collection of solar energy in space and its subsequent microwave transmission to Earth is one proposed option, involving Solar Power Satellites (SPSs) which feature very large structures covered with photovoltaic cells in space. Such SPS systems would enjoy almost 5 times more average insolation than terrestrial solar thermal power plants (1350 W/m^2 versus 300 W/m^2).

Renewed interest in SPSs has been fostered by the recent 'Fresh Look' taken by NASA at this application, which has generated a number of innovative architectural concepts and technologies aimed at reducing the required upfront investment. However, it is clear that even the 'Fresh Look' results do not show guaranteed economic viability. To be competitive with terrestrial solar power systems, a mass-specific power production of at least 200 W/kg, transportation costs of 1500 $/kg and hardware costs of 5000 $/kg are required for SPS systems. A configuration delivering a 500 GW output would cost about $44 000 billion (0.40 $/kWh). Much more advanced SPS systems may be possible in the distant future, at a projected total cost of $5600 billion (0.05 $/kWh).

In general, the attractiveness of SPS is strongly dependent on future launch costs, as well as on the rate at which innovations in the fields of, for example, microwave power transmission and large deployable structures become available. Even if SPS systems can be designed to be cost-competitive with terrestrial solutions, the technological demands and operational uncertainties would be immense. The recommended approach is therefore to proceed further with the development of generic technologies for large thermodynamic systems in space (NASA will do so with an investment of several million dollars a year), before re-assessing the economic affordability of SPS. For example, SPS elements may be derived from innovative Solar Sail technologies currently under development at DLR, as envisaged in the Sail Tower EuroSPS concept (Fig. 4).

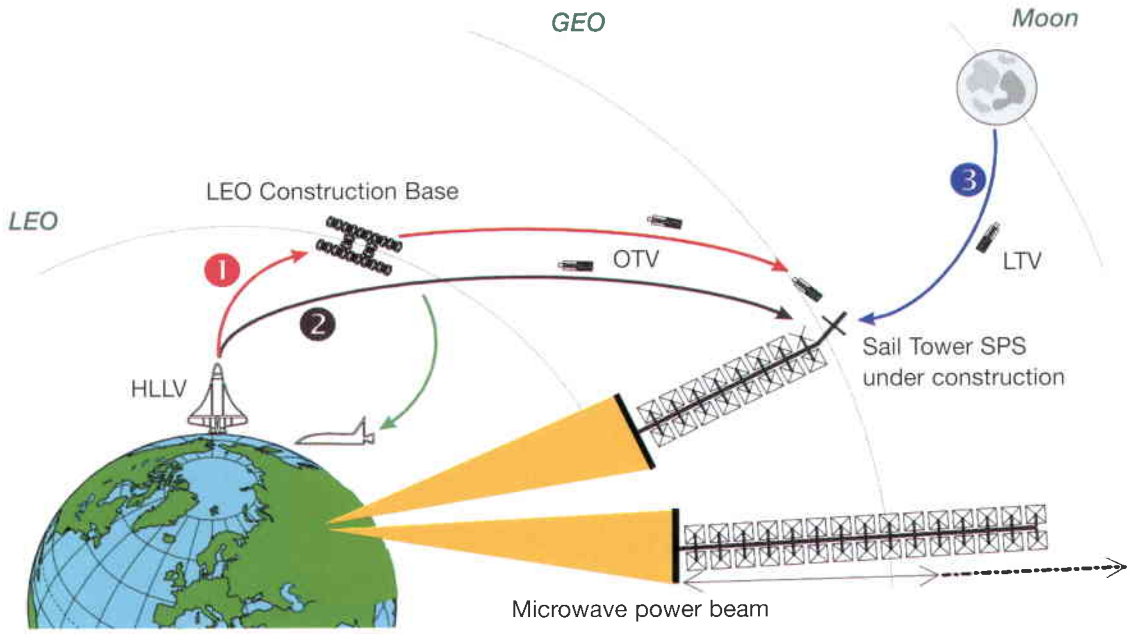


Figure 4. The Sail Tower EuroSPS scenario

A roadmap for the development of space solar power (Table 1) may start with experiments with wireless power transmission from the International Space Station (ISS) to a free-flying subsatellite with on-board scientific experiments. These could later be extended to experiments involving: satellite-to-satellite power transmission, including multiple receiving satellites in the vicinity of the ISS (e.g. for future satellite constellations); power supply to stratospheric platforms; power supply to planetary rovers and planetary remote stations. The next step may be wireless power transmission via a geostationary Power Relay Satellite (PRS), which could be employed to transmit energy produced by solar thermal power plants located in regions of high insolation, such as deserts, to other locations. PRS systems are inherently simpler and smaller than corresponding SPS systems, but the microwave power transmission technologies required would be similar. A cost-competitive European PRS system with a power output of 10 000 W/kg can be more easily envisaged than corresponding SPS systems.

Microwave energy from space could also be used for weather modification, including low-intensity applications (suppression or intensification of weather patterns such as cloud formations, and alteration of the ionosphere) as well as more extreme applications (e.g. modulation of severe storms). The feasibility of such long-term applications is unclear, due to the large uncertainties about the results of injecting energy into chaotic systems such as meteorological phenomena.

Space Tourism

The huge annual market for tourism on Earth ($3400 billion) has raised interest in the possibilities of 'Space Tourism'. Polls indicate that millions of people would be willing to spend up to $50 000 on a trip into space. To

Table 1. Roadmap for space solar power

Application	Main Features
Wireless power transmission experiments (ISS, satellite-to-satellite, stratospheric platforms, planetary surface)	Microwave-transmitted power at 2.4/5.8/35 GHz. Study of interaction of space plasma with microwave beam. Beam-steering, phase control experiments.
Power Relay Satellites (PRS)	Large reflector satellites in GEO. 10 GW microwave-transmitted power at 2.45 GHz. Increasing industrial involvement and commercial operations (ecologically driven).
Solar Power Satellites (SPS)	"Solar Power Towers" of modular design, gravity gradient-stabilised in GEO. Modular power generation from 7 MW to GW-level. Lightweight deployable or inflatable structures spreading sail-like solar array of thin-film solar cells. Microwave power transmission to ground at 2.45 GHz.

make this market accessible, a phased sequence of sub-scenarios (Fig. 5) beginning with sub-orbital flights on rocket planes, followed by short and later more extended Earth orbital tourism, can be envisaged.

As a first step, a rocket plane such as the Ascender concept should be able to take off conventionally, reach an altitude of 100 km with a crew of four, and return 30 minutes later. Assuming 15 000 annual flights and total costs of about \$3.8 billion for the development and production of, at least, 10 Ascender rocket planes, a profitable business might be established after about six years of operation with ticket prices of \$50 000. In the next phase, larger vehicles carrying typically 50 passengers, such as proposed in the Kankoh-Maru concept, could allow stays in orbit of several hours. Extremely high operations and serviceability demands must be met in order to carry out one launch per day. Again, operating costs are a dominant factor in the return-on-investment calculations, and estimated ticket prices of about \$50 000 may be too optimistic. Even longer stays may become possible in space hotels, which should provide accommodation for several dozen tourists at a time. However, at projected ticket prices of more than \$100 000 per visit, the market potential may be limited.

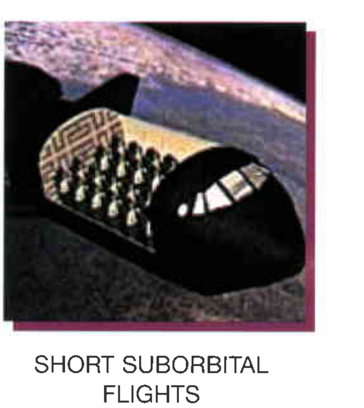
The need to break out of the conventional cycle of publicly financed space programmes, which suffer today from ever-decreasing budgets, is a major driver behind the interest in looking for a large source of income from the utilisation of space in the longer term, besides telecommunications and Earth observation. Hence the interest in the potential of space tourism. The main obstacles currently preventing space tourism from becoming a viable enterprise are high transportation costs, in the order of several tens of millions of dollars per trip, and safety considerations. A reduction of two orders of magnitude in the cost of transportation, to be achieved via reusable launch vehicles that can fly frequently and with low operating costs, is a common requirement for most long-term scenarios.

Technology Roadmap for SE&U

The diversity of the above SE&U scenarios calls for the development of a variety of capabilities and technologies to make them feasible. The technologies required for each scenario (Table 2) have been evaluated in terms of commercial, scientific and transfer potential, as well as with respect to public profile and status in Europe. Two broad classes of technologies can be recognised:

- Whenever a function linked to the acquisition and transmission of information is involved, technologies related to the miniaturisation of systems are important.
- Whenever the transportation and handling of large and heavy cargoes is involved (which is primarily the case for human missions), technologies related to large thermodynamic systems (i.e. propulsion, power, thermal management) are important.

As far as future space transportation and launcher evolution are concerned, the analysis has demonstrated the need for a fully reusable launch vehicle in order to achieve substantial reductions in space transportation costs. Semi-reusable vehicles are not promising from an economic point of view. Very optimistic estimates suggest that Earth to Low Earth Orbit transportation costs may ultimately be reduced to \$200/kg.



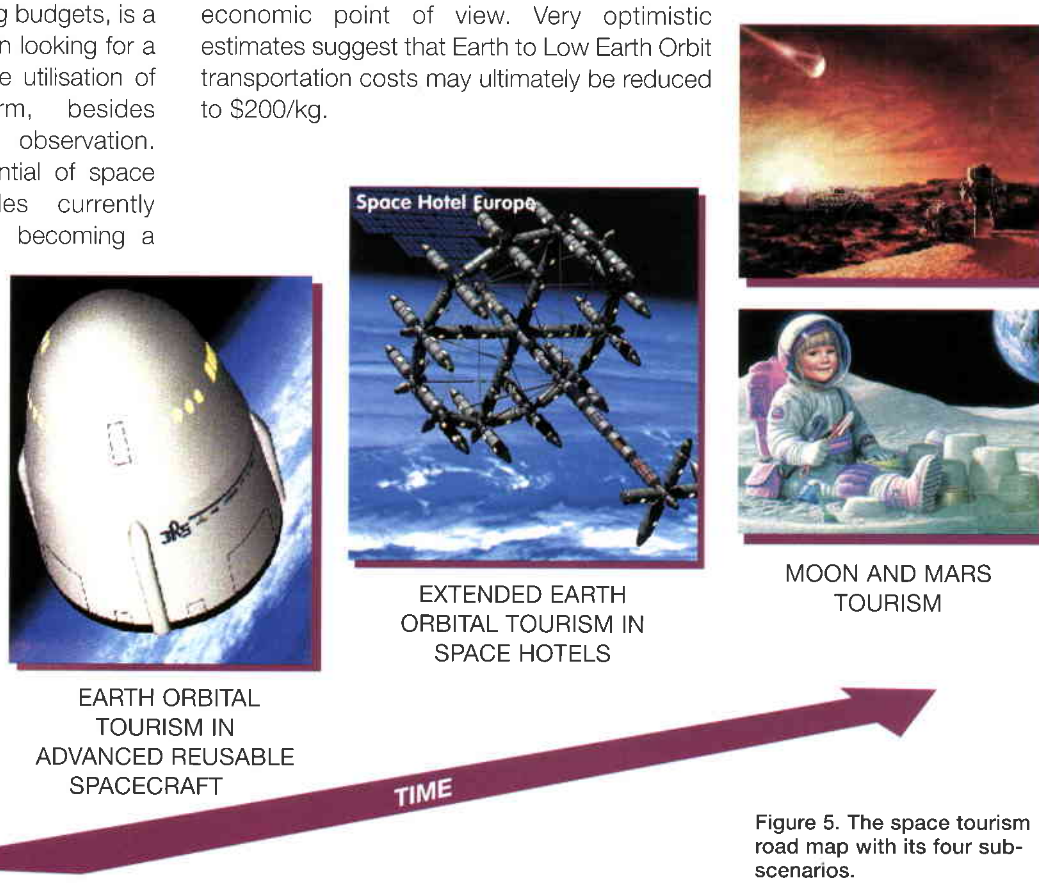


Figure 5. The space tourism road map with its four sub-scenarios.

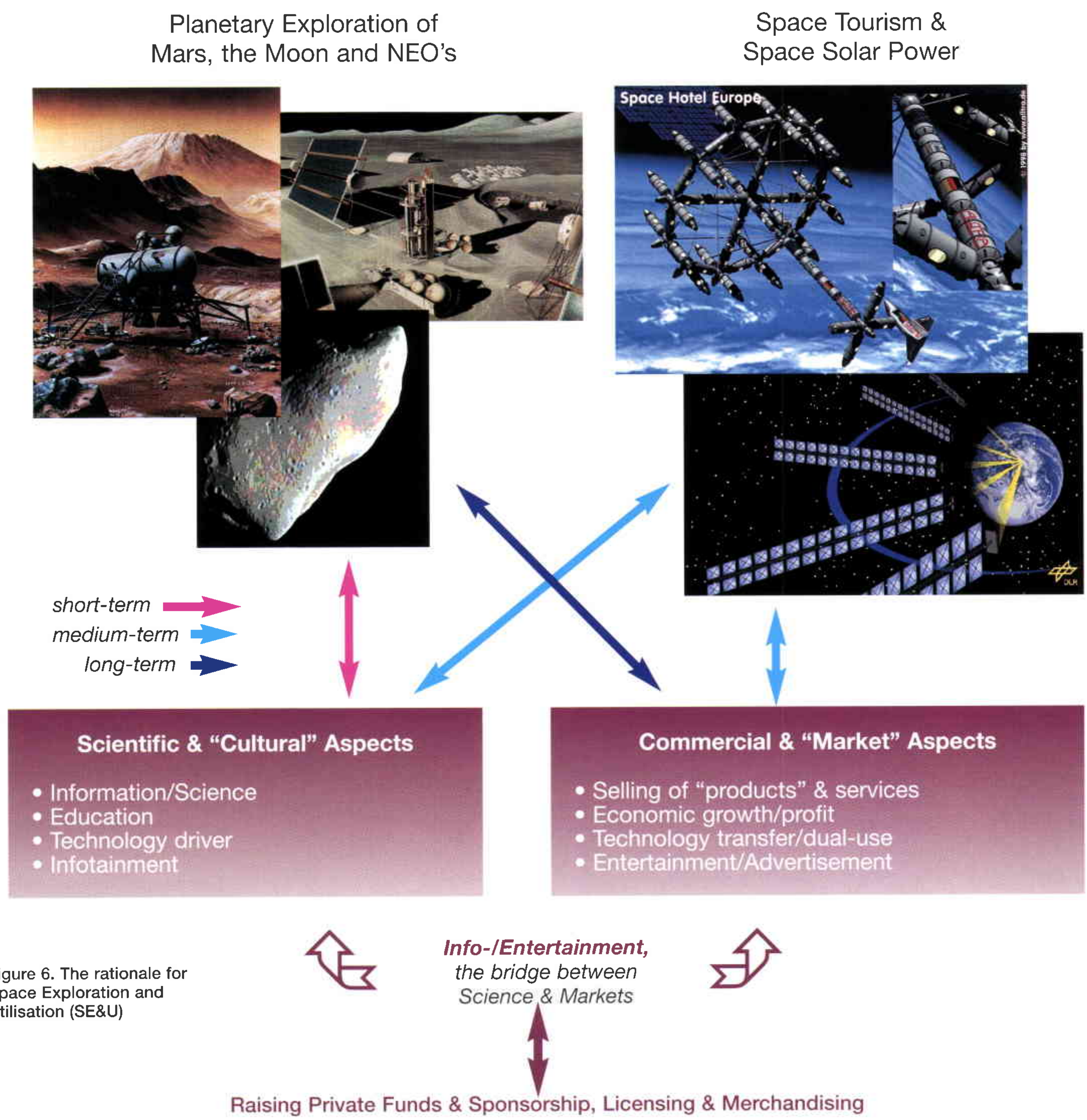


Figure 6. The rationale for Space Exploration and Utilisation (SE&U)

Conclusions and outlook

The exploration of planetary bodies including the Moon, Mars and Near-Earth Objects has tremendous potential for providing short-term scientific, educational and cultural benefits, but will certainly remain a largely non-commercial enterprise for the next two decades at least (Fig. 6). Currently, commercial activities are mainly hampered by the high costs of access to space, and thus launch-cost reduction is of the highest priority in order to make progress.

Considerable commercial potential has been identified for Space Tourism and Space Solar Power for the long term. The affordability and justification of Space Solar Power applications is significantly affected by the existence of terrestrial competitors for power generation, including regenerative options.

In the long run, the build-up of complex planetary infrastructures appears to be possible and may lead to a whole range of new markets and commercial activities. This should be a central consideration in the selection and development of capabilities during earlier missions. In a first step, the information/entertainment business may represent a bridge between science and the marketplace, which may be followed by more commercially attractive space products.

Table 2. Technology requirements for SE&U.

Type of System	Technology	Requirement	Applicability: Planetary Exploration (Moon, Mars, NEO's)	Space Solar Power	Space Tourism	Other Commercial Applications in Earth Orbit
Information-driven systems (miniaturisation)	Automation & Robotics	Mobile, highly autonomous systems, adapted to planetary surface environments. System lifetime in the order of decades, by replacement, upgrade, repair.	XX			X
	High-data-rate communications	Mbit/s level from Mars, supporting virtual reality and 3D visualisation applications	XX			X
	Micro-/nanotechnologies	Low mass, power, volume at system level.	X	X		X
	Radiation-hardened microelectronics	Mrad level.	XX	XX		XX
	Large-size structures	Inflatable and deployable, adapted to planetary surface thermal and mechanical environment. Lightweight, high-density packaging, self-deployable.	X	X		X
	Solar sail-propulsion	Large-size for large post-launch velocity increment. Deployment and control of very large structures in space.	X	X		
Mass-driven systems (large thermodynamics)	Cyrogenic propulsion	Specific impulse 450 s. Long-term in-orbit propellant storage. Reusability, throttleability.	X	X	XX	
	Nuclear thermal propulsion	Safety and control systems	XX			
	Electrical propulsion	High thrust (5N/thruster level). Lifetime 10 000 hours.	X			XX
	Aerocapture and aerobraking for entry and landing	Heat loads for entry from interplanetary trajectory, Lightweight thermal protection and hot structures. High-precision landing (<500 m).	X			
	Power generation, storage and conditioning	100 kW to MW level	X	XX		X
	In-Situ Resources Utilisation (ISRU)	Oxygen and propellant from lunar regolith and Mars atmosphere. Heavy-duty cooling and liquefaction systems.	XX			
	Advanced Life Support Systems	High degree of closure, and/or integration with ISRU. Bioregenerative systems	XX			

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INVESTING IN SPACE – *THE CHALLENGE FOR EUROPE*
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The ESA Council mandated the long-term Space Policy Committee (LSPC) to draw up a report on European Space Policy after 2000. Its First Report was unanimously endorsed by the ESA Ministerial Council in Toulouse in 1995 for providing valuable insight into the vast potential of future space exploration and exploitation and providing useful inputs to the evolution of European space policy and activities. The Ministers charged the LSPC to continue its deliberations and to submit a Second Report giving Member States a framework for long-term strategic thinking and decisions on European space policy.

This Second Report, presented to the ESA Ministerial Council in Brussels in May 1999, addresses three challenges that Europe faces at the turn of the century, challenges that will shape its nations' common future based on economic prosperity, quality of life, collective security and global solidarity. It contains a complete Action Plan, consisting of 20 specific actions, implementation of which is currently being further pursued, at the Ministers' request, by the ESA Council at Delegate Level and the ESA Executive.

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Technology Research and Development (TR&D) is a strategic enabling element of any space undertaking, whether commercial or non-commercial. The timely availability of the relevant technologies in Europe is a key factor in ensuring both the competitiveness and independence of the European space industrial fabric. TR&D is also a key element in the implementation of an overall space strategy. Europe has invested more than 150 billion Euro to date in the development of space programmes and their related technology. This investment, channelled mainly through ESA and national space agencies, has made it possible to create a strongly performing industrial base, competitive both in launcher products and services and in satellite markets at the global level.

Introduction

Today around 150 MEuro are spent by ESA every year on Technology Research and Development. Recognising the importance of helping other areas of industry to benefit from space activities, ESA launched its Technology Transfer Programme (TTP) in 1990. The main motivations included:
- Easing the burden imposed on public resources by TR&D by adapting space-engaged technologies, systems, and knowhow for other uses.
- Minimising duplication of research between the space and non-space sectors.
- Providing opportunities for researchers to collaborate with other organisations, both in spin-out and spin-in efforts.
- Maximising the return on investment in space research conducted by ESA for the benefit of its Member States.

The Technology Transfer initiative within ESA

The ESA Technology Transfer Programme aims to stimulate space spin-offs, i.e. secondary applications of the latest technological developments for space financed by ESA, its Member States and Canada. The prime objective is to ensure that non-space sectors can also benefit from easier access to advanced technologies. Another objective is to foster technology exchange, whereby space technology developers can learn from other sectors about their specific breakthroughs.

The achievements of space programmes are now so much a part of the economic, social and scientific scene that there is a tendency to forget their importance and the accompanying benefits for the industrial fabric as a whole, There is therefore a compelling obligation to promote the spread of space technology throughout the European Community, with the objective of integrating it into a market economy by adapting it to the latent demand.

ESA has set up a network, the 'Spacelink Group', with a correspondent in each Member State and Canada, responsible for:
- Technology Push: Europe-wide extraction and marketing of potentially transferable space technologies.
- Market Pull: determination of market demands in non-space industries and searching for space solutions.

More than 400 potential spin-off technologies have been marketed throughout Europe and Canada by the Spacelink network. More than 70 transfers of space technology to many sectors of industry throughout Europe have already been achieved, and significant economic and social benefits are beginning to accrue. At the end of 1999, space donor companies had received more than 4 MEuro in revenues from transfers, with receiving companies taking in more than 20 MEuro, and a projected turnover of 150 MEuro by the end of the year 2000 in both the space and non-space sectors.

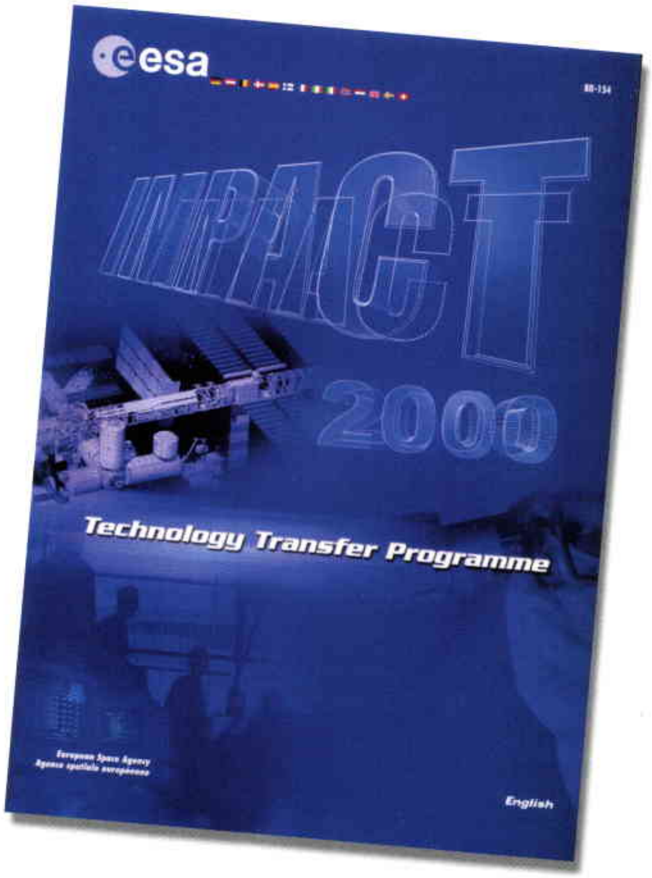
Technology push

Working in co-operation with ESA, the Spacelink partners are responsible for identifying and extracting transferable technologies from within ESA's technical establishments and space companies in the ESA Member States. The technologies selected must be well defined in terms of novelty, maturity, applicability, and intellectual property rights. Spacelink promotes these technologies via a catalogue, called 'Impact', with more than 40 000 European companies outside the space industry receiving copies.

Market pull
The Spacelink partners are also responsible for identifying and publicising the potential technology needs of non-space companies. Today, almost 6000 non-space companies have been approached about their technology needs, and more than 400 offers of solutions have been received from space companies as a direct response to these requests for assistance.

Additional support
Recognising that technology matching and licensing is only a part of the transfer process, the Technology Transfer Programme (TTP) and Spacelink are working actively with companies to fund and plan the development work necessary to move the technology closer to market. Not only has the programme helped to secure more than 10 MEuro of European Union support for research funding, but the TTP also selectively provides seed funding to companies, particularly small businesses, to enable them to perform feasibility studies for transfer projects. As part of the Spacelink network, the European Association of Research Organisations (EARTO) also works with potential technology recipients who need assistance in conducting research and completing various studies, including the identification of new non-space applications for space-developed technologies.

Industry initiatives
The TTP has developed industry-specific initiatives to promote exchanges between industry sectors and the space community, with the aim of finding new business solutions using space technologies and knowhow. A recent example of the type of work done in this arena has been an initiative directed at companies operating in harsh environments, particularly offshore oil and gas exploration and production, mining, and tunnelling. Since summer 1997, ESA has invested 1.8 MEuro in the development of the Harsh Environments Initiative (HEI), being led by the C-Core organisation in Canada (see ESA Bulletin No. 99, pp. 20-28). The HEI provides members of the space industry with an opportunity to learn about current and future technical challenges in this sector, and to present space technologies as possible solutions.



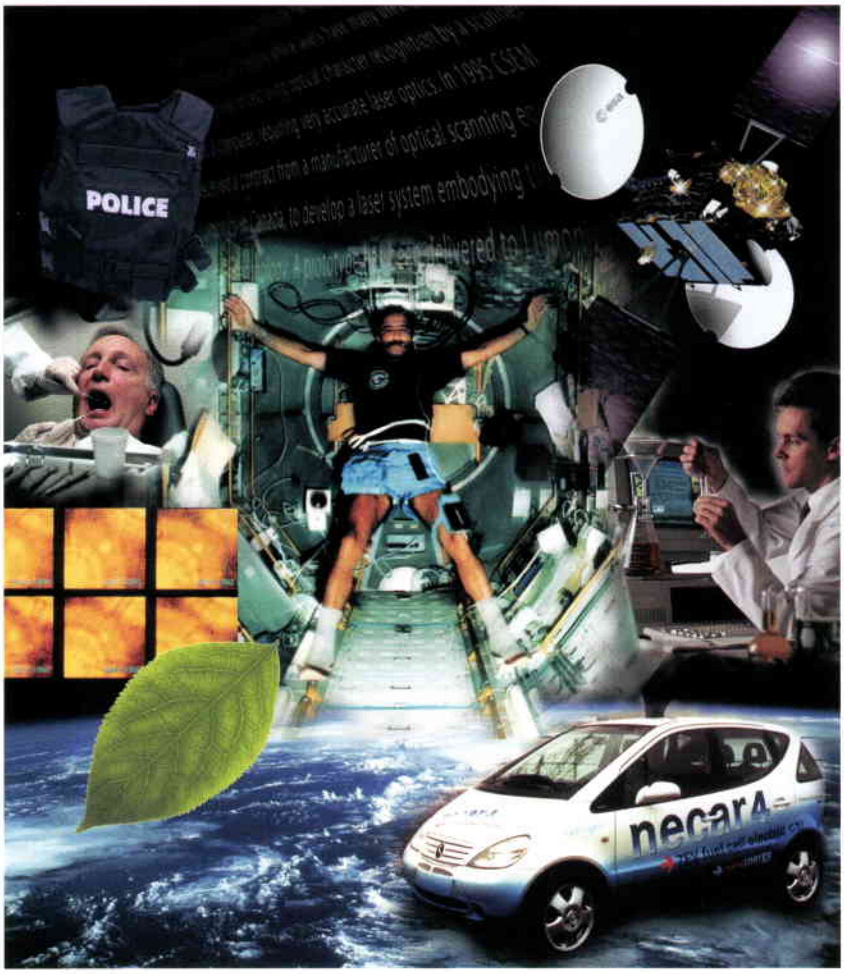
ESA initiatives supporting the TTP
Because only a part of the benefits from technology transfer are generated through physical transfers of technology and the licensing process, there are several further initiatives within ESA that contribute to the success of the TTP in areas such as knowledge transfer and collaboration.

The SME initiative
ESA has set up its SME (Small and Medium-Sized Enterprise) initiative with the dual aims of enabling ESA and European space industry to tap the potential of innovative SMEs, and opening up opportunities for SMEs in return to work more extensively with ESA and space contractors. Every precaution is being taken to avoid further fragmentation of the European space equipment supplier industry.

The initiative was approved by ESA's Industrial Policy Committee (IPC) in March 1998 for a two-year trial period. It was put on a more permanent footing by the Council at Ministerial Level's adoption of Resolution 2 in May 1999 in Brussels. The financial resources available for the SME initiative in 1999 were 1.7 MEuro from the General Budget and 0.5 MEuro from the Technology Research Programme (TRP).

In order to derive maximum advantage from synergy with other European programmes for SMEs, the definition of these enterprises applied in the ESA initiative is the same as that proposed by the European Commission in its Recommendation 96/280/EC of 3 April 1996. The initiative is therefore directed towards two types of SME: high-technology SMEs (normally small firms with close links to universities or research laboratories), and subcontractors to large groups:

- For high-tech SMEs, the initiative aims in particular to facilitate access to ESA's work and procurement plans. This reflects a conviction that they are able to bring an alternative perspective and act as vectors of innovation, as well as offer the potential for considerable improvements in synergy between space activities and other technical activities.
- For SMEs in general, the initiative includes various arrangements designed to improve the conditions under which they operate (access to information, access on terms to ESA technical facilities, opportunities for networking with other companies that might become customers or partners, etc.).



Among the different measures contained in the SME initiative, those actions aimed specifically at stimulating and encouraging SMEs as a source of innovation and synergies and technology transfer with other domains are further developed below.

Dedicated action for SMEs on Technology Transfer

The intention of this dedicated action is to foster diversification into other domains for SMEs that have already developed technologies for space applications. The support provided by the Agency is not only financial; depending on the particular circumstances, other types of support (technical, external) are also envisaged. A total 700 kEuro has been devoted in 1999 to this action, which can be complemented with additional means from other programmes, depending on the exact nature and origin of the transfer proposed. All contracts foresee a 50% co-funding by SMEs. ESA funding per contract has been limited to 50 kEuro. In order to broaden the industrial base, SMEs have been invited to submit only one proposal. An Announcement of Opportunity was issued (via ESA's EMITS electronic system) in May 1999, and closed on 29 October.

Thirty proposals were received from SMEs, thus confirming that this action responds to a clear industrial need. Of the thirty proposals received, fourteen have been retained for funding through the SME initiative and four by the Microgravity Programme. The proposals address many different technical domains, including materials (ceramics, composites), software (processing of image databases, evaluation tools), sensors and measurement systems, electronics, mechanisms, etc.

Specific support for unsolicited innovative proposals by SMEs

SMEs are invited to submit, at any time, innovative proposals for feasibility or adaptation studies (ARCOP programme). These activities (30 kEuro maximum) serve as an entry door for new, innovative companies, and the ESA Executive's first action is to put them in contact with companies already working for the Agency in the respective domains. The purpose of this action is therefore to revitalise the space sector with new, promising technical concepts coming from other domains, using SMEs as a source of innovation.

450 kEuro were foreseen in 1999 for this initiative, thus providing the possibility for some 15 innovative actions to be initiated. This initiative has also been announced on the EMITS system, but there is no time limit on applications: SMEs can submit ARCOP proposals at any time, and the industrial response is gradually increasing.

In order to implement the SME initiative effectively, a dedicated unit has been created within ESA's Industrial Policy Office in Paris (SME-Unit@hq.esa.fr).

Benefits from the TTP

Benefits from technology transfer can be wide ranging in nature, from increasing the financial revenues of companies to improving the quality of life of an individual. It is extremely difficult to develop a fully comprehensive list of the benefits accruing today from space technology transfers. This is largely because ESA does not rely solely on licensing, the easiest form of transfer to measure, but offers a broad range of mechanisms and tools that allow organisations to access and exploit European space-developed technologies and knowhow.

Economic benefits

By examining the market potential of transfers that are still in their early stages, ESA has estimated that returns to receiver companies will reach 500 MEuro by 2004. Donor-company returns are also expected to achieve exponential increases during that period.

Spin-off companies

Since the early 1990s, at least two small companies have been formed as a direct result of the TTP, creating employment opportunities for technically skilled employees. They have also been operating profitably within the first three years of start-up. One of the companies was created by an ESTEC engineer with expertise in simulating space missions using virtual-reality software. This software was also used to animate the motion of Hurricane Andrew, giving meteorologists a chance to understand better how the hurricane was formed and behaved.

Taxpayer return

Having calculated the direct economic benefits accruing from the TTP, it is also possible to estimate the indirect returns in terms of the additional taxes paid in the various countries due to the TTP-related growth in business, namely:

- 500 kEuro in taxes paid from donor-company profits
- 2 to 3 MEuro in taxes paid from receiver-company profits
- 7 to 8 MEuro in taxes paid on employees' salaries.

Other benefits

It is a well-established fact that cost savings are achieved by the companies that acquire and adapt space technologies for other uses. These savings encompass product-development costs, manufacturing and production costs, costs for training employees, and costs of protecting and ensuring employee safety.

Financial returns to ESA

Along with the 'softer' returns from the TTP, such as an increased awareness of ESA programmes and an increase in the capabilities and breadth of the space research base, ESA and the TTP also receive measurable economic returns.

Royalties

In cases where the intellectual property of a space technology is owned wholly by ESA, the Agency itself acts as the donor company and usually receives royalty payments. The best example of this type of revenue generation is the transfer of knowhow to industry through the general publication of a set of software standards that were developed by ESA for use by its contractors in large projects. These rules ensure that software being developed by different contractors at different locations have common specifications, design, validity, test and documentation. They were so effective and popular in ensuring that software was compatible and projects were successful that the contractors began using them even for non-space projects.

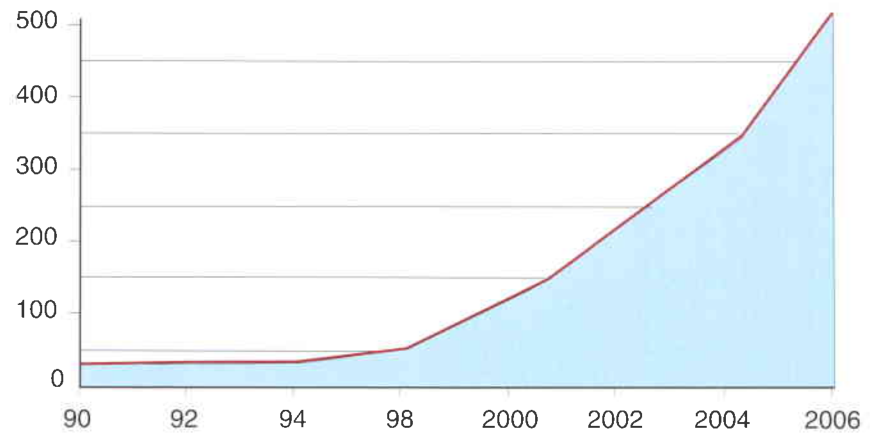


Figure 1. Cumulative turnover generated for receiving companies, in MEuro

Returns on investment

As mentioned earlier, companies have been benefiting from ESA and the TTP filling a gap in the European investment market by providing seed funding for the completion of feasibility studies and other research to validate the implementation potential of a particular technology transfer. Any company that receives seed money is required to reimburse a small percentage of its sales revenue to ESA in the event that the transfer is successful. Payments come in as a fixed percentage of sales until the amount invested has been recovered. Thereafter, a smaller (to be defined) percentage of sales is returned to ESA over the lifetime of the product.

Concrete examples

Space telescopes and the early identification of skin melanomas

A mathematical algorithm employed to analyse sets of X-ray data collected by space telescopes has been adapted for use in the early identification of skin melanomas.The algorithm has the ability to extract information from large and 'noisy' data sets, allowing it to identify previously unknown galaxies and other space objects. Researchers have adapted the algorithm into a tool that scans and magnifies the surface of the skin, and determines if cells and their structures have cancer cell characteristics. Doctors using this tool are more likely to detect and properly diagnose skin cancers at an earlier stage than with current techniques.

Space radiation and heart-disease treatment

The small British company Radiation Experiments and Monitors (REM), based in Oxford, has developed a Radiation-sensitive Field-Effect Transistor (RADFET) for ESA. The device acts as a radiation dosimeter, monitoring the cumulative or integrated dose of radiation for equipment in space. It has been used on unmanned programmes such as the Meteosat-3 meteorological satellite, and the Hubble Space Telescope. The simply designed silicon chip carries a layer of 'thermal oxide', which has been sensitised to ionising radiation (gamma-rays, hard and soft X-rays and high-energy particles). Radiation impinging on the sensor permanently changes the silica layer such that it acts as a record of the radiation received. A key advantage to the RADFET is that, as a micro-electronic device, it can send its 'integrated dose' signal through a cable or radio link and can thus be read out remotely.

When doctors find plaques and accumulations of cholesterol on the interior walls of arteries (arteriosclerosis), they often treat such patients using coronary angioplasty. A balloon catheter is inserted into the artery to open the blood vessels and so prevent coronary events such as heart attacks. In about 45 percent of patients, arterial blockages or closures re-occur during the healing process (restenosis) and the patient must undergo the procedure again.

Recent research has shown that irradiation can prevent the arteries from becoming blocked again. This involves inserting a catheter into the blood vessel, which is then exposed to beta or gamma-ray radiation in a treatment known as 'endovascular brachytherapy'. In order to control the degree of irradiation so as to prevent damaging the surrounding tissues while optimising the treatment, the amount of radiation applied in each layer of the tissue needs to be precisely monitored.

The solution, being developed by REM and IST, is to mount a RADFET sensor in the catheter in order to monitor the locations where radiation doses are to be delivered. The aim is to send the signal giving the accumulated radiation level to instruments that the medical team can monitor during treatment. Because the RADFET is so cheap when produced in bulk – less than 1% of the total cost of treatment – it can be thrown away after each procedure.

Diamond-like coatings for clearer plastics

When two components in a system rub together they create friction, which can wear out the components themselves and heat up the system. A small German company, MAT in Dresden, has developed a special diamond-like coating for treating bearings in the fuel pumps of the Space Shuttle. This coating is a carbon-based material with a molecular structure resembling that of a diamond. The advantages of the coating are its resistance to wear and scratching, its chemical stability, and the fact that it minimises friction in mechanical systems.

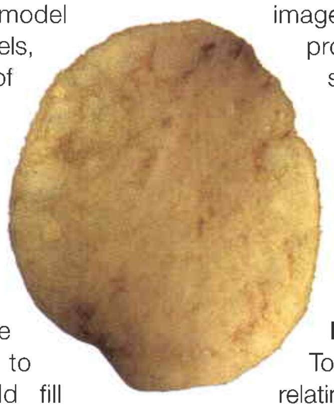
Plastic foils are manufactured using a large rolling mill, called a 'calendar'. The main parts of the calendar include the extruder, which mixes the polymer, and a series of rolls that transform the plastic material into sheets, or foils. Within the extruder, the granules of plastic are heated so that they melt and congeal into a continuous material. A key component of the extruder is a rotating worm, which mixes the material during this process.

Before the coating process was used, the surface roughness of the rotating worm caused the plastic to stick to it during mixing. The plastic stuck to the hot worm would then carbonise and crumble into the plastic mixture, forming black particles in the finished foils. Kalle Pentaplast, the World leader in plastic film and packaging, attempted to reduce sticking by coating the rotating worm with a variety of materials. Subsequent customer complaints about 'dirty' plastic increased Kalle Pentaplast's costs, particularly when orders had to be remade to meet customer specifications. Coating the rotating worm with the diamond film resulted in a significant reduction in residues.

The reduced friction between the coated rotating worm and the plastic material being produced also increases throughput in the extruder, because there is now less drag in the system. Each calendar can therefore produce about 10 to 15% more output than before.

'Landing' a potato crisp

The small German company Hypersonic Technology (HTG), in Grottening, specialises in solving aerodynamic flow problems for space projects. By observing how model spacecraft behave in wind tunnels, HTG can calculate the effects of very fast airflow on the motion, temperature and physical properties of space vehicles.



In 1998, MST – the German Spacelink partner – was challenged by an inquiry from a German packaging-machine manufacturer, Rovema, trying to develop a machine that could fill packets with lightweight food products, such as potato crisps, quickly and without breaking them. As the leader in the packaging-machine sector, Rovema must continually upgrade its wide range of machines in order to stay competitive. The constant search for ways in which to improve the performance of its machines led Rovema to explore space technologies and knowhow.

It was recognised that the scientific problem of dropping a potato crisp into a bag without breaking it is conceptually similar to landing a spacecraft safely. Both must take into account the optimum speed for a safe descent, and also consider how the flow of air affects the temperature, structure, speed and direction of the failing object.

Using the modelling, calculation methods and measurement knowhow developed through its work on ESA projects, HTG was able to develop a bagging system for Rovema which could be integrated into a new machine that can package foods 30 to 50% faster than existing equipment.

Rovema has tested a prototype model and anticipates that its new packaging machine, which received its first public viewing at the major international packaging trade-fair INTERPACK in Dusseldorf (D) in May 1999, will soon be mass-produced.

Conclusions

It has been proved that space-developed technologies can often find a place in non-space industries and products. In order to be transferred, however, these technologies frequently need to be adapted to cope with, or work optimally in, their new environment. Today, more and more support is being gained from industry, academia and government entities. The Agency's Technology Transfer Programme has demonstrated the economic viability of this powerful concept, having already resulted in several new business ventures in Europe. In addition to these concrete results, technology transfer is helping to foster the image of the European space programme. The slogan 'From space-developed technologies down to Earth' is now a reality within the European economic fabric, thanks to the ESA initiative, and European and Canadian SMEs, which are playing such a vital role.

Points of contact

To access and receive publications relating to ESA's Technology Transfer Programme, including the catalogues of transferable technologies and spin-off successes, visit the ESA Publications web site at:

http://www.esa.int/

Alternatively, you can contact the Technology Transfer Programme Manager or the SME Initiative Manager:

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The Certification of ESOC to ISO 9001

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On 30 November 1999, ESOC was awarded a certificate, confirming that it is compliant with the international quality standard, ISO 9001. ESA's Director General, Antonio Rodotà accepted the certificate from National Quality Assurance (NQA), an independent third-party registrar accredited by UKAS (UK), RvA (NL) and RAB (USA). ESA thus became the first space agency in Europe to have one of its facilities certified to ISO 9001.

This article describes the justification for certifying ESOC to ISO 9001, the activities leading up to the certification, the immediate consequences for ESOC and ESA, and concludes by describing the key lessons that were learned from this initiative.

What is ISO 9001?

ISO 9001 is an internationally recognised standard for the definition and implementation of quality systems for the design, development, production, delivery and servicing of any type of product or service provided by one organisation to another. ISO 9001 specifies requirements that determine what is called 'a quality system'. The quality system encompasses:

- Management responsibilities: ensuring adequate delegation of responsibility and authority, allocation of resources and control of the quality-system implementation.
- Implementation of controlled processes: addressing requirements definition, design, production, verification and validation, delivery and post-delivery support for all products and services.
- Support elements: such as documentation control, procurement control, internal auditing and corrective actions.
- Documentation of the quality system: in a Quality Manual and associated procedures.

The quality-system requirements specified in ISO 9001 are generic and can be applied to any products or services in any industry. The ISO 9001 requirements do not address technical performance requirements for any product or service. These are defined separately and agreed between the customer and supplier. In the case of ESOC, performance requirements for satellite operations services are defined either in a contract, for external customers such as Eumetsat, or in internal documents called the Mission Implementation Requirements Document and the Mission Implementation Plan, which are approved by the Project Manager of the relevant ESA project.

Figure 1. ESA's Director General, Antonio Rodotà (left), the chairman of NQA, David Johnstone, and ESA's Director of Technical and Operational Support, David Dale

Why certify ESOC to ISO 9001?

It was decided to certify the Centre to ISO 9001 to increase the confidence of all its customers in the quality of the work and the results supplied by ESOC, and to increase the confidence of all ESOC stakeholders in the efficiency of the internal operations. This will complement the proven ESOC technical excellence and improve the competitiveness of ESOC in the global satellite operations market.

ISO 9001 was selected because it is the single most widely adopted standard for quality management in the World. It is, in many ways, considered the 'gold-standard' for quality management in international commerce. There is a well-defined system for independent assessment and registration by nationally accredited certification bodies. Since this system is recognised by companies and governmental organisations worldwide, customers of ESOC can have a high level of confidence in its work processes and outputs. Use of other standards, such as PSS or ECSS, or only internal verification of ISO 9001 compliance by ESOC would not provide the same level of confidence to these customers.

Specifically, this increased level of confidence was expected to be achieved by improving:
- Focus on customer needs and expectations: resulting in increased quality of ESOC products and services.
- Clarity of work processes: including roles, responsibilities and interfaces, resulting in improved efficiency.
- Focus on problem prevention: resulting in reductions of effort and cost to achieve the desired results.
- Traceability of actions and results: resulting in increased visibility and confidence of ESA management in ESOC quality management practices.

The importance and value of certifying ESOC to ISO 9001 was emphasised a year after the start of the project by the ESA Council decision in December 1998, allowing ESOC more freedom to compete in the commercial space operations market. In commercial markets, certification to ISO 9001 is becoming a necessity to compete effectively.

Preparation and start of work

Discussions over several years between various staff in ESOC and members of the Product Assurance and Safety Department culminated in the submission of a proposal for the establishment of a formal quality system in ESOC in the summer of 1997. At the request of David Dale, ESA's Director of Technical and Operational Support (D/TOS), this proposal was extended to include certification of the ESOC quality system to ISO 9001. The proposal was approved in November 1997 by David Dale and the Department Heads involved, and preparatory work began. The schedule for the ESOC certification project is shown in Figure 2.

A Steering Group was formed, composed of the Director and Department Heads and two representatives of ESA projects who are customers of ESOC services. One representative was appointed from ESA's Science Directorate and one from its Applications Directorate. The Steering Group was to direct the work, monitor progress, approve the quality system and give the approval for implementation of the quality system in ESOC.

A Working Group was also formed, chaired by the Head of the Quality, Dependability and Safety Division, and consisting of representatives from all Divisions and key work groups in ESOC, including the ground stations at Redu and Villafranca. Senior expert staff with extensive experience were selected for this assignment. The Working Group was responsible for developing the ESOC quality system, supporting the implementation of the quality system, and preparing for the certification activities (Fig. 3).

The Working Group held its first meeting in December 1997, and created the key plans necessary to define and control the work. The Certification Project Plan defined the roles and responsibilities of those involved in the effort, key project activities and the schedule culminating in a planned certification of ESOC by the end of 1999. The Communications Plan

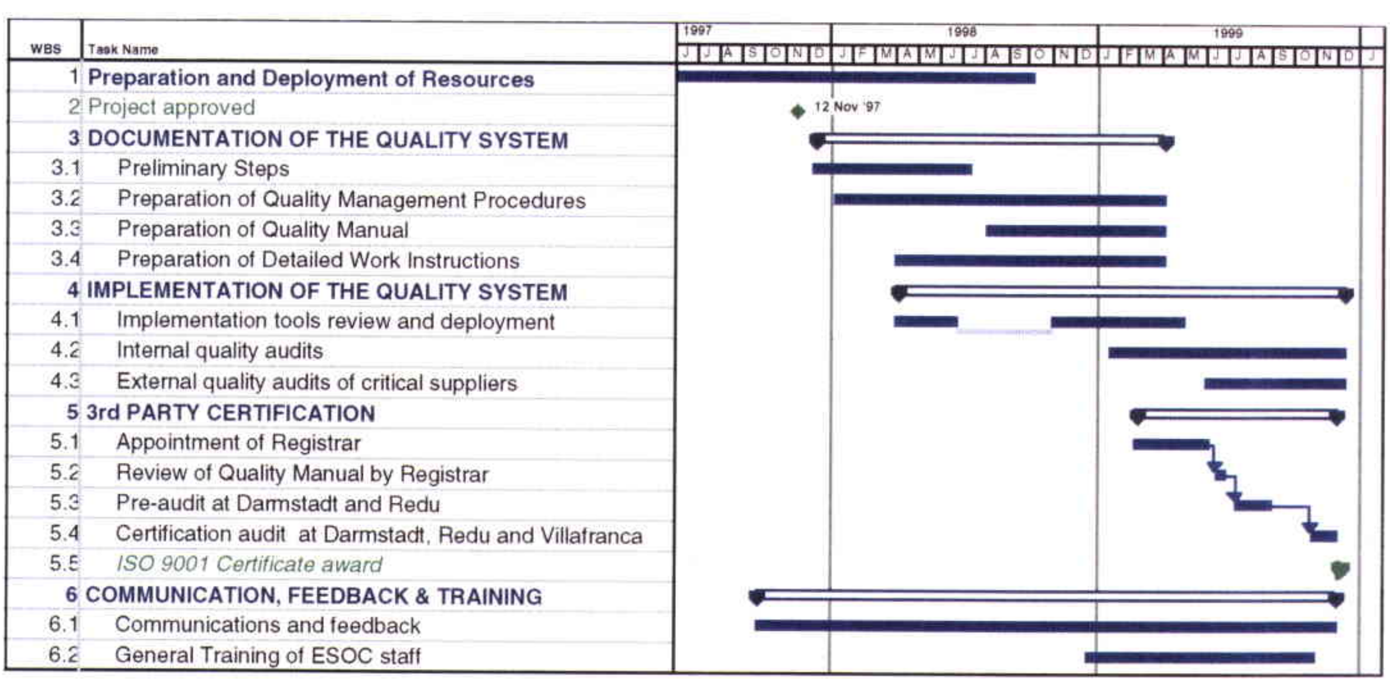

Figure 2. Schedule of ESOC certification project activities

complemented the Project Plan by identifying the responsibilities, methods and activities to communicate the certification progress to the staff of ESOC. Early in the project, a logo (Fig. 4) was designed for the project and was used on all staff communications.

Development of the ESOC quality system
The Working Group followed a logical sequence of activities to develop the ESOC quality system. ISO 9001 requires that the customer needs and requirements form the starting point for any supplier activity. Therefore, the Working Group began by identifying all the internal and external customers of ESOC, and what products and services the Centre provides to these many customers. This list of products and services evolved over many months.

Figure 3. Members of the ISO 9001 Working Group

As each entry in the list of products and services was firmly agreed, the Working Group assigned tasks to sub-groups to define all the processes, activities and the interfaces with groups outside D/TOS involved in the development and provision of that product or service. These sub-groups often included additional experts needed to clearly define and understand the detailed implementation of the process.

As soon as each process was documented and approved by the Working Group as a whole, the relevant sub-group drafted the related procedures and other documents to be included in the ESOC quality system. Each of these documents underwent a two-phase review process. Each document was first reviewed by the Working Group to ensure it was correct and consistent with other documents. Then each document was submitted to a public review in ESOC, in which all affected staff could comment on the document and request changes.

The implementation of every public review comment was agreed in dedicated meetings in which the reviewers were invited to participate. The documents were then updated according to the agreed disposition of the comments and the revised document was approved by the Steering Group and released for implementation by ESOC.

The resulting ESOC quality system has four levels (Fig. 5):

- Level 1 is the Quality Manual, which serves as the 'road-map' to the ESOC quality system. It defines the ESOC Quality Policy, defines the relationship and implementation of all procedures in the quality system, and describes the relationship of the ESOC quality-system elements to the ISO 9001 requirements.

- Level 2 are procedures describing generic processes common to multiple ESOC activities or groups (e.g. ground-segment design, configuration management) These procedures define roles and responsibilities, inputs, activities, outputs and interfaces with other processes.

- Level 3 are work instructions defining the implementation details of a portion of a Level 2 procedure, or the specific implementation of a Level 2 procedure in a particular area of ESOC. Document Requirements Definitions are also considered Level 3 documents.

- Level 4 are quality records in ESOC. Quality Records document the performance of an activity, such as an audit report, or the results achieved, such as a test report. Most Quality

Figure 4. Logo for the ESOC certification project

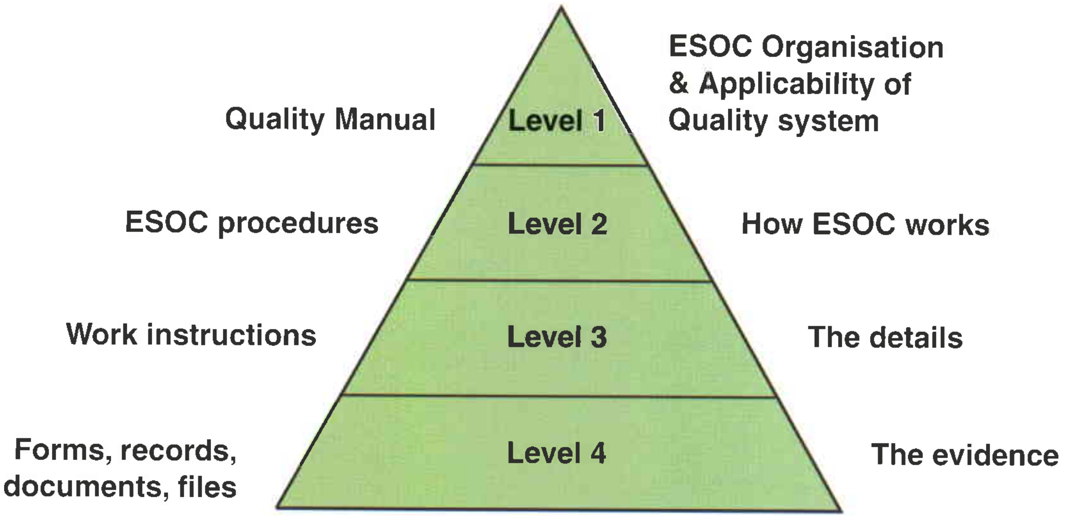

Figure 5. ESOC Quality System Document levels

Records defined in the ESOC quality system are based on documents already generated and used within ESOC. The quality system procedures simply formalised the creation and contents of these documents.

In September 1998, the Quality Manager, a new position at ESOC, took up his duties. Initially, he assisted in the ongoing development of the quality system and in preparing for the roll-out and implementation. As the Steering Group approved each quality-system document, it also specified the start of application in ESOC. The quality-system procedures were progressively made applicable starting in January 1999.

Roll-out and implementation
Every effort was made to ensure that the quality system incorporated existing methods of working in ESOC. Inevitably, however, some existing methods had to be changed and some new practices were introduced. Accordingly, it was recognised that the entire ESOC quality system could not be retrofitted into every existing ESOC project. The roll-out policy defined by the Steering Group required that the ESOC quality system be applied to all new ESOC projects from 1 January 1999 onwards, and that it should be applied to existing projects where deemed appropriate by the ESOC Ground Segment Manager concerned. Projects not using the entire ESOC quality system were encouraged to use portions of the quality system to the maximum extent feasible.

The preparations for roll-out involved:
- informing the staff of the procedures, initially by presentations and subsequently by specific training
- ensuring that essential support tools, particularly for documentation management, would be available
- verifying implementation of the procedures by means of audits
- establishing the first improvement teams.

As the ESOC quality system is unique to this Centre, it was recognised that, although the Working Group members had the best understanding of the content needed in training courses, they lacked specific skills to develop and deliver such courses. Consequently, Working Group members received training for this activity, and then developed the necessary course materials and delivered the training to ESOC staff. The Quality Manager prepared the training plan, ensured that each staff member received the training they needed according to their responsibilities, managed the scheduling of the courses, and maintained the training records. Training was conducted during the summer of 1999 and was completed in September.

The Quality Manager planned and managed the internal audits of the ESA quality system. Audits of all areas of ESOC were conducted from the beginning of 1999. In the first phase, there were two rounds of audits in each area

ESOC Certification Facts Sheet

QMS Documents	:	**74**
Internal Quality Audits	:	**46, all areas audited twice**
External Audits	:	**5 (critical suppliers)**
Training Attendance	:	**852 attendees in 71 classes**
Projects with formal PA	:	**Envisat, Mars Express, MSG, SMART, Rosetta, XMM**
Manpower booked	:	**~ 2 m/y in 1998 ~ 3 m/y in 1999**
People involved	:	**128**

from January to September. The first audit in each area was conducted to ensure that the applicability of each procedure was correctly defined and known by all staff, and to ensure that the records required for each audit were known and were available. The second round of audits began the process of actually verifying the implementation of the quality-system procedures. Following this first phase, the strong and weak areas of implementation were assessed. The results of this assessment were used to guide the planning for the subsequent audits.

Audits of external suppliers critical to the success of ESOC were also conducted during this period. The results of these audits have been used to identify improvements to be discussed with relevant suppliers and also to ensure that appropriate levels of management and supervision are applied to each critical supplier.

As the work progressed, areas of potential improvement were identified. Improvement teams were formed for two issues in 1999 – Documentation Management and Configuration Management (CM). The formation of improvement teams will be a continuing feature of the ESOC quality system.

The Documentation Management Team conducted an inventory of existing tools and identified the documentation management needs in all parts of ESOC. Some existing tools, such as the Documentation Management System, have been upgraded for use in ESOC. Local tools to manage anomaly, non-conformance and problem reports continue to be used as an interim measure, pending the development of a common tool for the whole of ESOC.

The Configuration Management Team investigated the application of CM in ESOC and identified that this function is distributed over all parts of the organisation. Control is effective, but is applied at the local level. There is no harmonised system-wide identification and reporting of the Ground Segment configuration. Work is continuing to define the requirements for the consistent identification, recording and reporting of configuration information on the Ground Segment as a whole.

Certification

The certification process started in June 1999. Following selection of the registrar for ESOC, a copy of the ESOC Quality Manual was reviewed by the external auditor. Then, in July, the auditor visited ESOC for a three-day pre-audit inspection. During this visit, the auditor met with selected staff from every functional area of ESOC, in Darmstadt and in Redu. The auditor performed the same activities intended for the certification audit, though in a less detailed way.

The findings from this visit enabled the Quality Manager and the Working Group to identify potential problem areas and implement corrective actions to ensure that ESOC would be ready for a successful certification audit. The Steering Group approved the corrective action plan resulting from this process and monitored its implementation.

Finally, after two years of hard work, the certification audit was held at the end of October. Some minor non-conformities were identified, but the auditors were confident that the ESOC quality system functions properly and is under control. The ISO 9001 certificate was presented to ESA's Director General at ESOC on 30 November 1999 (Fig. 6).

What comes next?

In ESOC

For ESOC, the ISO certification is not an end, but a beginning. The quality system that has been defined includes provisions for the active monitoring and assessment of quality-system performance and, most importantly, continuous improvement. Not only must ESOC continue to demonstrate that the procedures of the quality system are being followed correctly, but it must continue to improve those methods and procedures.

Mechanisms are in place to enable any staff member to identify and propose improvements. Inputs from customers are also used. Twice each year, the Director of Technical and Operational Support, the relevant Department Heads and the Quality Manager meet to review the quality-system performance and the results of existing improvement teams. During these reviews, further improvements, including the specific actions to be taken to achieve those improvements, are identified.

In ESA

During the roll-out of the ESOC quality system, others parts of ESA began to hear about this initiative and requested additional information, in some cases leading to discussions of how to implement a similar initiative elsewhere in the Agency. As a result of these contacts, it was decided that the Earth Observation Applications Department at ESRIN will begin its ISO 9001 certification initiative in early 2000. This is expected to result in certification during 2001.

Discussions are also being held regarding the possibility of having the whole of ESA certified to ISO 9001. This would result in many desirable benefits, including:

- greater clarity of roles and responsibilities for all staff within the Agency
- greater confidence of Member State Delegations in the efficiency and effectiveness of ESA
- greater transparency to the ESA Council of the Agency's functioning
- improved interfaces, contacts and management methods for projects contracting with European industry.

Benefits

Although operation of the quality system has only recently started, ESOC staff have already noticed benefits from this initiative, including:

- Clarity of roles, responsibilities and activity flow: leading to the elimination of bottlenecks, identification of critical areas and faster decision making.
- Clarity of project requirements in early phases of the work: leading to reduced discussion and disagreement with customers.
- Focus on prevention of problems: leading to fewer problems, less reworking, faster throughput and lower costs.


NATIONAL QUALITY ASSURANCE

Certificate of Registration

This is to certify that the Quality Management System of

EUROPEAN SPACE OPERATIONS CENTRE – (ESOC)
ROBERT-BOSCH-STRASSE 5, 64293 DARMSTADT,
FEDERAL REPUBLIC OF GERMANY

INCLUDING THE CONTROL CENTRE IN DARMSTADT, GERMANY AND THE GROUND STATIONS IN VILLAFRANCA DEL CASTILLO, SPAIN AND REDU, BELGIUM

applicable to

THE PROVISION OF SERVICES RELATED TO THE OPERATION OF SPACECRAFT, INCLUDING THE DESIGN, IMPLEMENTATION AND OPERATION OF GROUND SEGMENTS, THE PROVISION OF GROUND SEGMENT AND COMMUNICATIONS SYSTEMS, IN ORBIT PAYLOAD TESTING AND SERVICES RELATED TO SPACE DEBRIS, CONSULTANCY AND FLIGHT DYNAMICS

has been assessed and registered by
National Quality Assurance Limited against the provisions of

BS EN ISO 9001 : 1994

This registration is subject to the company maintaining a quality management system, to the above standard, which will be monitored by NQA.

The Seal of National Quality Assurance Limited was hereto affixed in the presence of:

Managing Director

Certificate No: 10631

Date: 8 November 1999
Valid Until: 7 February 2003

EAC Code: 31

015

The use of the UKAS Accreditation Mark indicates accreditation in respect of those activities covered by the accreditation certificate number 015 held by National Quality Assurance Ltd. National Quality Assurance Ltd is registered in England. Registration No. 2209505. Registered Office: Vintage House, 37 Albert Embankment, London SE1 7UJ

Figure 6. The ESOC ISO 9001 Certificate

- Fact-based decision making: situations are now better documented, leading to fewer disagreements based solely on opinions.

Lessons learnt

During the development and roll-out of the ESOC quality system, many lessons have been learnt, some of the most significant of which are summarised below.

Management structure / involvement

Active involvement of management at all levels is important, but the commitment of top management is essential. There were several issues that required the intervention of the Director and his Department Heads to resolve problems. Without these interventions, the success of the project would have been questionable.

The Steering Group was a significant contributor to the project success. Participation by the customer representatives from ESA projects in the Steering Group was a positive factor. They helped the Steering Group to remain focused on the customer objectives. The fact that customer representatives participated in the Steering Group helped to convince some staff early in the project that this was a serious initiative.

Figure 7. ESOC QMS home page on the Web

Training

It was found that significant amounts of training are essential for success. Unfortunately, the Working Group members did not receive adequate training at the start of the project. Consequently, the early results were disappointing and slow in coming. On the positive side, training of ESOC staff regarding implementation of the quality system was extensive and extremely successful. Staff members responded enthusiastically to the training and offered many suggestions for improvements to the courses and to the quality system itself during the training.

WG participation

It was found that a Working Group to establish and roll out the quality system with wide participation of staff from all areas of ESOC was essential for success. All affected groups, possibly including external groups with important interfaces, should be represented in the Working Group. It is also important to include as many senior experts from the organisation as possible. These experts, inevitably, are extremely busy, but they ensure that the majority inside the organisation will accept and implement the results.

Progress measurement

Measurement of work progress is necessary to ensure adherence to the project implementation plan, and to ensure that problem areas are identified and resolved quickly. During the first half of 1998, progress was slow until a simple but effective method to measure progress was developed. After a progress measurement method was agreed, it was always the first order of business in Working Group meetings to identify what was achieved, and the last order of business to identify what progress was required to be achieved by the time of the next meeting. This kept everybody focused and motivated during the sometimes difficult period of developing the more than 70 documents that collectively define the ESOC quality system.

Communication

Communication at all levels and during the entire project is fundamental and necessary to combat negative attitudes. Enthusiasm and public support from the top management of the affected organisation are critical. ESOC was very successful in its communication efforts. With the active support of the Public Relations office, a communications plan was developed during the first months of operation, enabling a wide variety of communications activities to be conducted. All meetings and public communications were well supported by the Director and the Department Heads.

A web site was created during the development of the ESOC quality system, which was used to make documents available for review and to support the communications with staff. This web site has been upgraded to provide relevant information to ESOC staff regarding the system and its use. The ESOC QMS home page is shown in Figure 7.

Conclusion

In closing, the authors would like to thank all those who participated in the development, roll-out and implementation of the ESOC quality system. It was a pleasure and a great learning experience. We are confident that this initiative will institutionalise the continuous improvement of ESOC, and will thus contribute to securing the Centre's future in the space operations business.

Laser Radar for Scientific Space Applications

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Active optical sensors based on laser light are key devices for range measurement in space. Laser radars employing the time-of-flight technique cover applications spanning the entire ranging distance spectrum, from topographic mapping to rover navigation. A laser radar programme initiated back in 1991 for the development of key technologies and techniques has yielded several novel concepts and demonstrators. Both mechanically scanned sensors and very fast non-scanning devices have been investigated and breadboarded.

With the recent delivery of the Active Surface Imaging System (ASIS) and test-bed, another major milestone has been achieved in sensor technology by combining fast image acquisition and broad range together with high spatial resolution. ASIS can capture 300 x 300 pixel images over a 60 deg x 60 deg scan range within 15 seconds. As a commercial spin-off, industrial devices have confirmed the design's potential for further extending the scanning range up to 80 deg x 340 deg, with a typical working distance of a few hundred metres.

Introduction

As part of its long-term programme in Space Science, ESA is currently investigating a number of deep-space missions involving the dispatch of space probes to planetary bodies or comets for close-up surveying, in-situ measurements by rovers, and the return of sample material to Earth. Mars, the Moon, Mercury, and Venus exploration missions are typical examples.

Pulsed direct-detection laser systems are the ideal choice for making reliable distance measurements in space, thanks to their low complexity, excellent performance and high instrument layout flexibility. The lidar principle makes use of short light flashes emitted by a laser source hitting a target and being backscattered to a detector. The time that the laser pulse takes to travel from the transmitter to the receiver is precisely counted, allowing calculation of the target's distance with millimetre accuracy. Laser sensors can also be readily optimised for any given mission scenario, making them very attractive for a wide range of applications.

An added benefit is that laser sensors can be operated conveniently from both orbiting spacecraft and planetary landers, putting comparatively modest requirements on spacecraft resources in terms of mass, size and electrical power. Active optical instruments can advantageously complement or extend the capabilities of passive optical imagers or microwave radars. Laser sensors can play an essential role in mapping planetary surfaces for selecting a safe landing site. Being active instruments, they can provide measurements from both the dark side and the sunlit portion of a celestial body, thereby significantly increasing the useful observational coverage.

Laser sensor developments

In 1991 an ESA frame contract was initiated with Dornier Satellitensysteme GmbH (DSS) covering the development and breadboarding of imaging laser radar technology and demonstrators. A consortium was formed, composed of the German companies Dornier Satellitensysteme GmbH, Dornier GmbH, Silicon Sensors GmbH, and Daimler Chrysler Aerospace Raumfahrt-Infrastruktur and two Austrian companies, Riegl Laser Measurement Systems and Joanneum Research. The various activities conducted were funded initially through the ESA Technological Research

Programme (TRP) and later by the ESA General Support Technology Programme (GSTP).

The first activity, on Laser Sensors for Planetary Research (LSPR), covered sensors for future solar-system exploration missions. Demonstrators were produced operating over a distance range from zero to 1 km. A sensor was tailored to the Cometary Approach and Landing System (CALS) forming part of the Rosetta scientific mission. Typical tasks were topographic mapping prior to the landing of a probe and support to the descent and landing itself. However, the Rosetta mission has since been descoped somewhat in terms of landing tasks and the CALS laser sensor will no longer be required.

The next activity dealt with Application of Frequency-Modulated Continuous-Wave Laser Radars (FMCW) in 1992. The goal here was to analyse and experimentally validate the frequency-modulated laser radar concept for long-range applications on planetary and cometary space missions. A representative demonstration model was realised, including different laser sources with good coherence lengths.

The consistent follow-on step was to further miniaturise the laser-ranging technology based on pulsed lasers. The Miniature Laser Sensor (MLS) study investigated that aspect in 1993.

Work on a Demonstrator of an Advanced Laser Sensor (DEAL) was started in 1995. The objective here was to design, manufacture and test a pulsed laser sensor demonstrator for near-range applications like rover vehicles or rendezvous and docking. Strong emphasis was put on mass reduction, rapid image acquisition and the scanning capability. In parallel with the DEAL work, a first step towards a fast electronic scanning system was initiated with the development of an avalanche photodiode line array with narrow gaps between the 64 pixels.

An Advanced Surface Imaging System (ASIS) was the next demonstrator activity in 1996, putting considerable effort into achieving an extended scanning range, fast image acquisition times and measurement repeatability. A well-defined test-bed with calibrated reference targets was established and used to calibrate the sensor. In addition to the ranging images, a Digital Elevation Model (DEM) was also processed online. ASIS formed the reference sensor for the test-bed and can be compared there with other active, as well as passive imaging sensors.

The latest activity has been to investigate a Scanner-less Range Imager (SRI) relying on a new laser ranging concept based on pulsed lasers and a CCD-camera with electronic shutter as receiver. This non-mechanical scanning concept provides an enormous range of image acquisition rates, together with high lateral resolution in the near range.

Applications

Laser radars are able to cover all distance ranges, from several hundred kilometres (for topographic mapping, atmospheric measurements), through the middle ranges (for cometary or planetary approaches), down to very short ranges (for rendezvous and docking). Depending on the laser technology used, pulse energies from hundreds of nano-Joules up to a few hundred milli-Joules can be achieved. Nadir-looking devices for topographic mapping as well as mechanically and electronically scanned sensors have been realised. Some potential applications are as follows:

Long-range applications (>100 km)
- Topographic mapping of planetary and cometary surfaces (Mars Observer Laser Altimeter, Clementine, Moon, Mercury, Venus)
- Topographic mapping of asteroids (Near-Earth Asteroid Rendezvous, Clementine)
- Ice-sheet topography (Geoscience Laser Altimetry System)
- Acquisition of land-topography and vegetation data samples (Shuttle Laser Altimeter)
- Measurement of cloud and aerosol layers in the atmosphere (Shuttle Laser Altimeter, Atmospheric Light Detection and Ranging).

Mid-range applications (up to 20 km)
- Topographic mapping of celestial bodies for the selection of landing sites (Moon, Mercury, Venus)
- Detailed mapping during descent
- Support of landing probes.

Short-range applications (below 1 km)
- Rendezvous and docking of spacecraft with the Space Station
- Navigation, obstacle warning and recognition systems for rover vehicles
- Manipulation in space (object-grasping missions)
- Distance measurement for satellites flying in formation (X-Ray Evolving Universe Mission - XEUS)
- Monitoring of baseline lengths in interferometric Synthetic Aperture Radar (Shuttle Radar Topography Mission)
- Monitoring of large antenna structures in space (International Space Station, surface-profile monitor).

The main projects

Laser Sensors for Planetary Research (LSPR)

This very first activity initiated a series of laser sensor demonstrators and breadboards within a dedicated frame contract. The sensor that was developed can perform topographic mapping to select a landing site and can support the landing of a probe on a comet. The main emphasis was on the development of the basic technologies like transmitters, receivers with high dynamic range, and precise range measurement.

Two different laser heads were developed to cover the wide range of distances. A Q-switched diode-pumped Nd:YAG rod laser delivers a 50 µJ pulse energy and provides range data a few kilometres from the comet. The landing itself is guided by a pulsed diode laser with 80 nJ pulse energy and higher repetition rate. Range is measured by determining the time of flight with the aid of a digital counter. The return signal is sampled and analysed to extract all available data. Pulse energy, peak power and pulse width are extracted. A coaxial optical arrangement of transmitter and receiver beam has been realised with dichroic beam splitters.

Strong cross-talk from the 50 µJ transmitter during the laser firing requires a receiver front-end and range-measurement unit with a dynamic range of 160 dB. This high dynamic range is achieved on a pulse-to-pulse basis. The detector is electronically protected against optical overload and thus cannot be destroyed by reflecting or bright targets. The heart of the range measurement unit is the trigger circuit detecting the short pulse returned from the target. A zero-crossing device is employed as an essential improvement over the frequently used constant-fraction stage. A small portion of the transmitter beam is coupled out to a reference receiver giving the start event for the time measurement. High range precision is achieved by counting the round-trip time with a low clock frequency of 15 MHz combined with a time-to-time conversion technique based on pulse stretching by a factor of 500. All stages involved in the time measurement process showed internal delays depending on temperature and signal intensity, and so both parameters are measured and appropriate corrections applied. The range images were acquired with a mirror galvano scanner unit.

Table 1 highlights some of the LSPR's primary features, while Figure 1 shows details of the experimental set-up used for testing the devices.

Table 1. Main characteristics of LSPR laser radar

Solid-State Laser Transmitter	q-switched diode-pumped Nd:YAG at 1064 nm
laser mode	TEM_{00}
pulse energy	51 µJ
pulse duration	13.5 ns
repetition rate	500 Hz maximum
Diode Laser Transmitter	pulsed current, wavelength 850 nm
pulse energy	80 nJ
pulse duration	24 ns (MOSFET switches)
repetition rate	50 kHz maximum
Range Measurement	time-to-time conversion with post-correction
dynamic range	160 dB on a shot-to-shot basis
distance range at 1064 nm	200 m – 10 km
distance range at 850 nm	5 – 500 m
standard deviation	less than 20 mm at high SNR
maximum measurement rate	1 kHz
Transmitter Budgets	
Nd:YAG Unit	
mass	4.7 kg
volume	5.2 l
power demand at 1 kHz pulse repetition frequency	16.8 W
Diode Laser Unit	
mass	3.4 kg
volume	3.7 l
power demand at 1 kHz pulse repetition frequency	3.6 W
Receiver and Range Measurement Unit Budgets (1064 nm or 850 nm, both units nearly identical)	
mass	2 kg each
volume	2.9 l each
power consumption	10.8 W each
Pulse Analyser Unit Budgets	
volume	19.8 l
power consumption	12 W

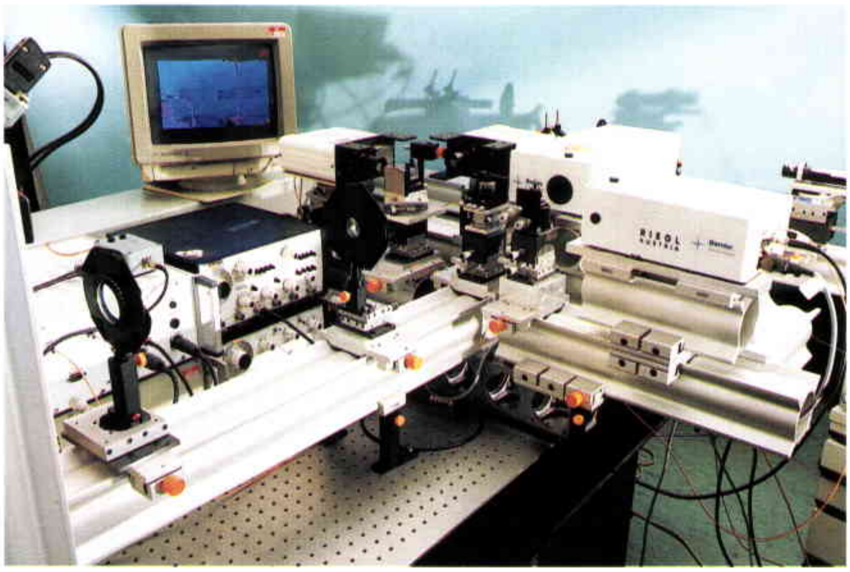


Figure 1. LSPR hardware and experimental set-up

Application of Frequency-Modulated Continuous-Wave Laser Radars (FMCW)

This project aimed at the development and validation of a frequency-modulated laser radar for long-range applications on planetary and cometary space missions. The chirped transmitter laser is mixed in a homodyne receiver set-up with the signal backscattered and delayed by the target. Due to the round-trip time, a low-frequency signal occurs that is directly proportional to the target distance. A demonstration breadboard was built, including a laser source with good coherence length, the receiver, related optics and a FFT-analyser. Furthermore, the breadboard was equipped with two diode-pumped Nd:YAG rod lasers with an internal electro-optic phase modulator and piezo-activated resonator mirror.

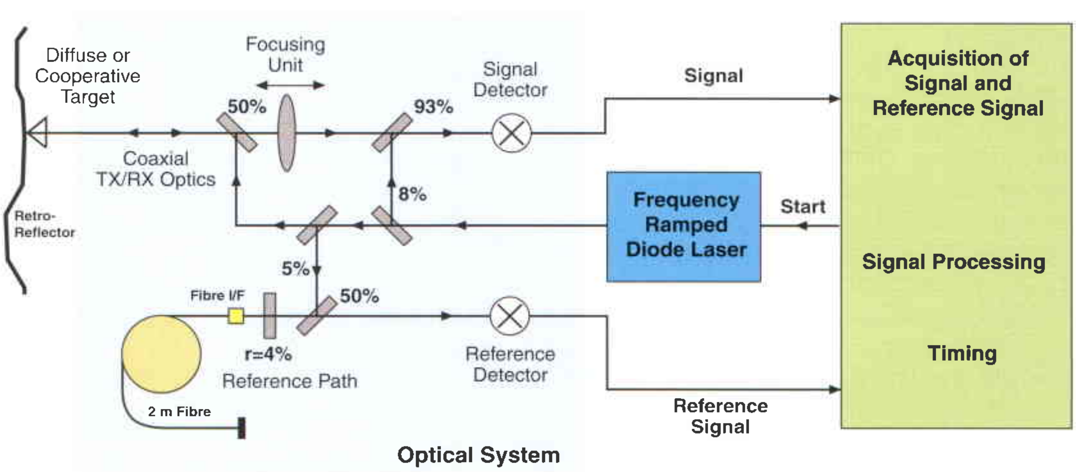
One significant result achieved was the demonstration that range measurements are possible even if the target distance exceeds the coherence length of the laser. However, the study also showed that the frequency-modulated laser radar principle has no significant advantages compared to the time-of-flight method. Targets have to be in focus to the lidar, there are restrictions on the target properties, and the overall set-up and data processing seemed to be too sensitive and complex at that time.

The configuration of the FMCW demonstrator is shown schematically in Figure 2. The experimental set-up of the breadboard is shown in Figure 3.

Demonstrator of Advanced Laser Sensor (DEAL)

This project also focussed on pulsed laser radars, and particularly on further miniaturisation and with a strong emphasis on the scanning device and fast image acquisition. Potential applications are support to navigation systems on rovers or rendezvous and docking sensors, all operating at ranges of up to a few hundred metres. The modular design involves an electronics unit and a separate scanner unit connected via optical fibres. A compact notebook computer collects the sensor data via its parallel port and displays range and intensity images in real time. DEAL is therefore a conveniently portable, easy-to-use and easy-to-set-up active ranging and imaging system.

Figure 2. Schematic of the experimental FMCW breadboard



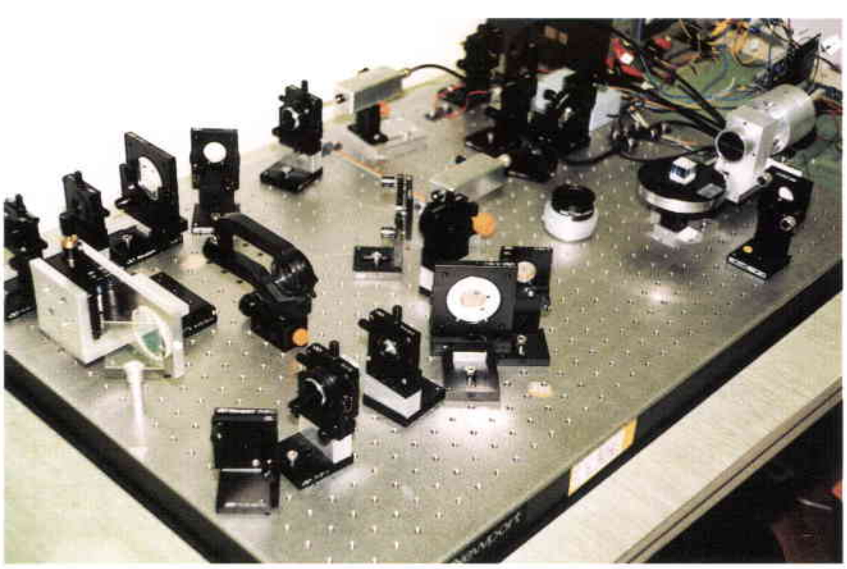


Figure 3. FMCW laser radar optical breadboard

The laser transmitter is based on a single-stack pulsed diode laser running at a high repetition rate. Short laser pulses of 8 ns duration ensure high basic range resolution. The diode laser is driven by a parallel chain of avalanche transistors, in contrast to a slower metal-oxide semiconductor field-effect transistor (MOSFET) design used in previous projects. The start event for the time-duration measurement is taken directly from the electrical signal firing the laser. No thermoelectric temperature stabilisation is foreseen, which helps to keep the power consumption low.

The direct-detection receiver employs a silicon avalanche photo-diode (APD) with stabilised bias. The detector is electronically protected against optical and thus also electrical overloads. The APD's signal is amplified by a trans-impedance amplifier realised in discrete technology to give a wide dynamic range and fast recovery at strong light levels in the near range. A line interference filter suppresses background radiation.

A full scan range of 20 deg x 5 deg was realised by linear vertical mechanical movement of the fibre ends in the optics focal plane. A slower horizontal scan was performed by a re-direction mirror in front of the common optics, turned with the aid of a stepper motor. Range measurements are based on the time-of-flight technique, combined with time stretching as mentioned before. The basic clock speed was increased to 1.3 GHz, yielding a range error of only 6 mm at high signal-to-noise ratio. Using a modern micro-controller, the measurement rate could be increased to 12 kHz.

The important features of DEAL are summarised in Table 2, whilst Figure 4 shows the actual hardware. The notebook computer is not required to operate the device; it just collects and saves the sensor data and displays the range images.

Advanced Surface Imaging System (ASIS)
This development activity was aimed at the further improvement of a mechanically scanning laser radar, with strong emphasis on a larger scan range, better spatial resolution and faster range image processing. The sensor was again tailored to application ranges of up to a few hundred metres. The capabilities of ASIS could be demonstrated in a dedicated test-bed equipped with several calibrated mobile targets of different shapes, reflectivities and textures.

The hardware is divided into one electronics unit and a fibre-coupled scanner unit. ASIS provides data on range, intensity, and both scan angles at a parallel interface to a standard personal computer. Every pixel of the image is coded by 8 bytes. Quick visualisations of range and intensity images alone are given in real time on the computer's display. The final data product is a Digital Elevation Model (DEM), including also the measured scan angles. It is calculated via another software module and can be displayed in real time also.

The laser transmitter uses a triple-stack pulsed diode laser. Paralleled avalanche transistors generate short pulses. The laser diodes are not stabilised in temperature. The backscattered light is converted to current by an APD in a direct-detection receiver. An optical interference filter suppresses background radiation. The photodiode is protected against overload and its bias is stabilised over temperature. The received signal's amplitude is sampled and logarithmically processed. This information, together with the measured temperature allows the raw range result to be corrected to achieve centimetre precision. The drive pulse of the laser diode triggers the round-trip time measurement and the first zero-crossing of the received pulse after exciting a resonant circuit stops it. A time-to-digital converter consisting of a circular counter chain with gate delays evaluates the time-of-flight. The position of the stop pulse within that chain is detected.

Table 2. Main characteristics of DEAL laser radar sensor

Diode Laser Transmitter	pulsed current, wavelength 905 nm
pulse energy	170 nJ in fibre
pulse duration	8 ns (transistor switches)
repetition rate	15 kHz maximum
Range Measurement	time-to-time conversion with post-correction of temperature and signal fluctuations
dynamic range	130 dB on a shot-to-shot basis
trigger method	zero-crossing network
distance range for natural targets	0 – 250 m at reflectivity of 0.4
standard deviation	6 mm at high SNR
maximum measurement rate	12 kHz
Scanner Unit	
fast scan	scan angle fixed to 5°
slow scan	scan angle 20° up to 30°
acquisition time of image (50 x 200 pixels)	2 sec
Electronics Unit Budgets	
mass	2.4 kg
volume	2.6 l
power demand	9.2 W
Scanner Unit Budgets	
mass	3.6 kg
volume	3.7 l
power demand	16.1 W

Figure 4. The DEAL hardware

Table 3. Measured results and characteristics of ASIS laser radar sensor

Diode Laser Transmitter	pulsed current, wavelength 905 nm
diode type	3-layer stacked device
pulse energy	270 nJ in fibrepulse
duration	9.2 ns (transistor switches)
repetition rate	24 kHz maximum
Range Measurement	time-to-digital conversion with post-correction of temperature and signal fluctuations
dynamic range	130 dB on a shot-to-shot basis
trigger method	zero-crossing network
distance range for natural targets	0 – 300 m at reflectivity of 0.4
standard deviation	16 mm at high SNR
maximum measurement rate	22 kHz
Scanner Unit	
fast scan	scan angle fixed to 60°, angle resolution of 0.04 grad
slow scan	20° up to 90°, angle resolution 0.02 grad
acquisition time of image (300 x 300 pixels)	15 sec for 60°x 60°
Electronics Unit Budgets	
mass	2.5 kg
volume	2.6 l
power demand	7.0 W
Scanner Unit Budgets	
mass	5 kg
volume	6 l
power demand	12 W

The fast scanner employs a rotating polygonal wheel with four facets. The scan range is therefore limited to 60 deg in this direction. The slow scan is made by rotating the entire movable part of the scanner unit with the aid of a stepper motor. The movable section includes the fast scanner and the biaxial optics. The concept chosen results in a very compact scanner with an extended scanning range. In addition, the design has the potential to provide a scanning range of up to 80 deg x 340 deg.

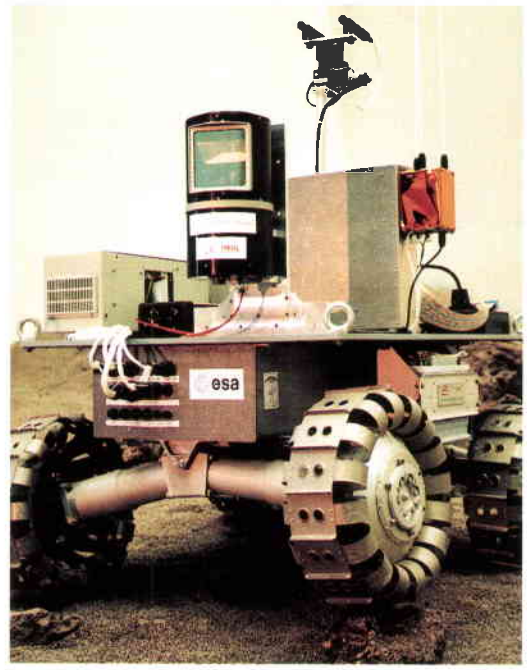
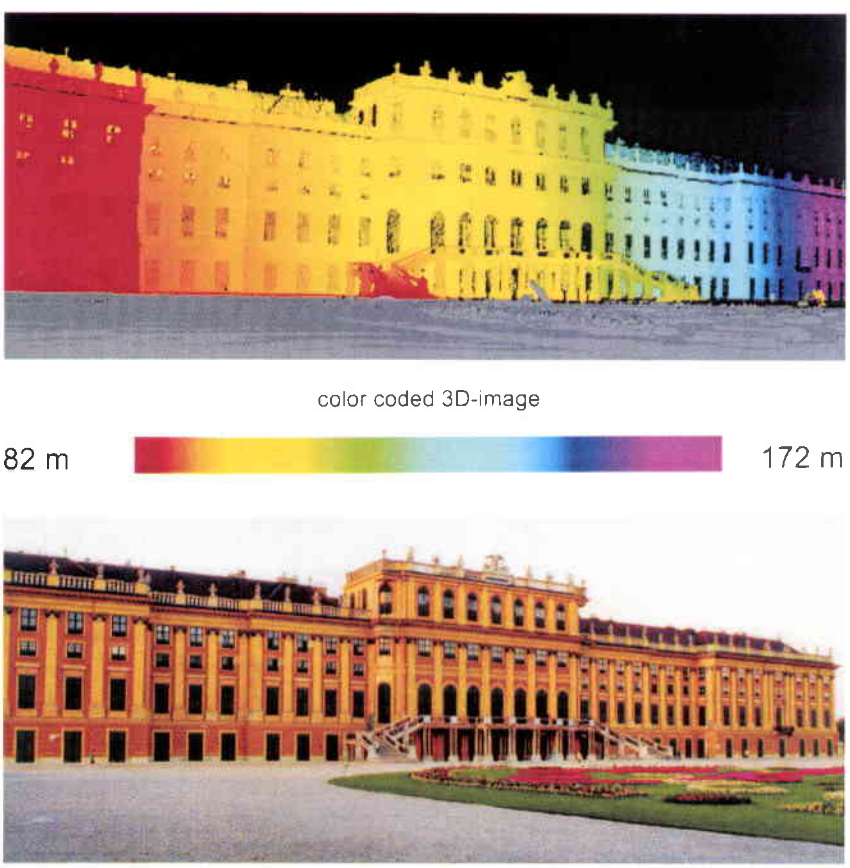


Figure 5. ASIS mounted on a rover as part of ESA's Planetary Utilisation Test-Bed

Figure 6. The Imperial Palace of Schönbrunn in Vienna (A) as imaged by ASIS



A commercial device with that scan range has recently become available as an industrial spin-off from the ESA work.

Table 3 summarises the major characteristics of the sensor, whilst Figure 5 shows ASIS mounted on a Lunar Rover Mock-up as part of ESA's Planetary Utilisation Test-Bed (PUTB). A typical commercial measurement product is shown in Figure 6, which is an ASIS image of the Imperial Palace of Schönbrunn in Vienna, Austria.

Scanner-less Range Imager (SRI)

A new type of imaging laser radar for short-range applications makes use of a CCD-camera equipped with a progressive scan interline transfer CCD-array and a fast electronic shutter which is part of the array's architecture. By synchronous detection of modulated laser light, the intensity of the received light is converted to range information. The pulsed laser source illuminates the entire scene by expanding its beam. Background radiation is subtracted from range information and the processed ranging image is then normalised to compensate for the varying reflection coefficients of a target. So in fact three images are taken and reduced to a single calibrated range image. The scan range is determined by the field-of-view of the laser source and CCD-camera. No moving parts are involved in the very fast scan process. Limitations of the technique are the restricted dynamic range of today's CCDs and the reduced distance range of several tens of metres. Image resolutions of 640 x 480 pixels are standard and range image rates of 10 Hz can be achieved. As the light intensity of the spread laser beam is very weak, several hundreds up to thousands of laser shots are averaged on the CCD prior to the final read-out of the result. Recently, a prototype of the patented concept has been realised by DASA-RI, Bremen (D). Key objectives of the first investigations in the Scanner-less Range Imager (SRI) project were to characterise the prototype's performance and to identify possible improvements with a view to future space applications.

Table 4 lists the important features of the SRI, and Figure 7 shows the miniaturised systems without the control unit.

Conclusion and outlook

The investigations into laser radar developments for scientific and operational space applications described here have clearly shown that pulsed laser systems have the best application prospects. The modular active optical sensors offer high measurement precision and fast measurement speeds, with low system complexity. For certain tasks, the active sensors are clearly preferable to the stereo vision systems currently being used. Furthermore, clear spin-offs could be derived for commercial ground-based applications involving observation and surveying. Alternatives to the more conventional opto-mechanical scanning devices for close-up operations will be studied further in the light of future space applications, looking to acquire three-dimensional imaging information with small, lightweight devices similar to a standard digital CCD-camera.

Table 4. Main characteristics of the Scanner-less Range Imager

Diode Laser Illuminator	pulsed current, wavelength 850 nm
diode type	5-layer stacked device
pulse energy	1.5 μJ
pulse duration	10 – 100 ns
field of view	10° x 8° up to 42° x 32°
Range Measurement	light intensity converted to range information, 12 bit quantisation
dynamic range	1:4000
distance range for natural targets	0.5 – 30 m at reflectivity of 0.5
standard deviation	less than 2% of range cell
maximum measurement rate	6.7 Hz for 640 x 480 pixel or 10 Hz for 320 x 240 pixel
SRI Sensor Budgets	Camera with Laser
mass	0.60 kg
volume	0.85 l
total power demand	75 W (incl. control unit)

Figure 7. The miniaturised SRI system

Electric Propulsion: A Key Technology for Space Missions in the New Millennium

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Electric propulsion is currently considered a key technology for the new generations of commercial and scientific satellites. Initiatives in this field all over the world are aimed at the development and space validation of new electric-propulsion systems and the rapid implementation of this technology on new spacecraft. In Europe too, space agencies and industry are setting up collaborations to accelerate and optimise the procurement of electric propulsion. The goal of this effort is to maintain the competitiveness of European industry in the space field, by ensuring the availability of qualified and reliable electric-propulsion systems, and to make new and challenging scientific missions possible. ESA is strongly involved and committed in this technology area, both as an initiator of electric-propulsion system developments and a user of this technology for its new missions.

What is Electric Propulsion?

Electric Propulsion (EP) is a class of space propulsion technologies which make use of electrical power to accelerate a propellant by means of electrothermal, electrostatic or electromagnetic processes. The use of electrical power enhances the propulsive performances of the EP thrusters compared with conventional chemical thrusters. Unlike chemical systems, electric propulsion requires very little mass to accelerate a spacecraft. The propellant is ejected up to twenty times faster than from a classical thruster and therefore the overall system is many times more mass efficient.

Compared with chemical propulsion, EP is not limited in energy, but is only limited by the available electrical power. Therefore, EP is suitable for low-thrust (milli-newton levels), long-duration applications on board spacecraft. The propellant used in EP system varies with the type of thruster and can be a rare gas (i.e. xenon or argon), a liquid metal (i.e. caesium or indium) or, in some cases, a conventional propellant such as hydrazine, or similar substances (i.e. ammonia, nitrogen, etc.).

Although studied, developed and tested for several decades, electric-propulsion systems have not been readily employed so far in space applications mainly due to the unavailability of sufficient electrical power on board the spacecraft. The availability today of constantly increasing levels of electrical power on all types of new spacecraft allows the use of EP to be seriously considered, and the era of application for this technology has finally arrived.

Based on their physical method of operation, EP systems are classified according to three main categories:
- Electrothermal (resistojets, arcjets, etc.)
- Electrostatic (gridded ion engines, Hall-effect thrusters, field-emission thrusters, etc.)
- Electromagnetic (magnetoplasmadynamic thrusters, pulsed plasma thrusters, etc.).

Depending on the specific field of application, thrusters falling into one of these three categories can be more or less attractive, depending on their particular thrust capabilities, electrical power consumptions and other propulsion performance characteristics. The levels of development and flight heritages of the different thruster types can vary significantly. In Europe, developments have been carried out in all the different areas of electric propulsion over the last three decades. Now that the operational use of EP has finally been accepted, the potential users are in the process of both selecting current EP technologies for immediate use and defining requirements for the new generation of EP systems to be used in Europe in the longer term.

The main applications of EP systems

In summary, the current domains of application for EP systems, are:
- Geostationary Earth Orbit (GEO) telecommunications
  - station-keeping
  - orbit transfer
- Low Earth Orbit (LEO) telecommunications constellations
  - orbit transfer
  - drag compensation
  - orbit and attitude control
- Interplanetary missions

- Scientific and Earth observation missions
  - ultra-fine pointing
  - orbit and attitude control
  - drag compensation (including drag-free spacecraft).

The commercially most important and therefore the driving application domain for the use of EP so far has been GEO telecommunications, where it is already in operational use in Russia and in the USA, while Europe will start to use EP for this application in the year 2000. The use of EP on this class of satellite for in-orbit station-keeping purposes and for the transfer to the final geostationary orbit, makes it possible save several hundred kilograms of propellant. This saving eventually results in a significant economic advantage, by allowing the use of a smaller and cheaper launcher, by allowing an increase in the mass of the commercial payload, or by allowing the extension of the satellite's operational lifetime.

Following this lead, the use of EP for other application domains is now attracting great interest. In particular, the most important constellations of telecommunication satellites in LEO are currently being designed to use electric thrusters to perform the transfer to the operational orbit and other functions. Thanks to the mass savings made possible by the use of electric propulsion, fewer launchers are needed to place the constellation in orbit, thereby allowing a major cost reduction for the service being offered.

Electric propulsion is also being adopted by several scientific and Earth observation missions, where this technology will be used to provide the primary propulsion functions or to perform highly precise control operations. Thanks to electric propulsion, interplanetary and deep-space missions will be performed within shorter trip times and with more scientific payload on board than conventional missions relying on chemical propulsion and complex planetary fly-bys. Moreover, sophisticated new scientific missions, such as space interferometers and drag-free constellations, will become feasible by using EP thrusters capable of providing extremely low and accurate thrust levels.

The importance of electric propulsion for future European space missions is already well recognised and ESA is supporting technology development of EP systems and components as a demonstration of the commitment of European industry in this field of technology. Recently electric propulsion has been recognised by Eurospace, the organisation representing the European companies working in the space sector, as one of the ten top technologies where investments are needed to enhance and maintain European industry's competitiveness in the space field.

Figure 1 provides a snapshot of the various potential fields of application for European EP systems.

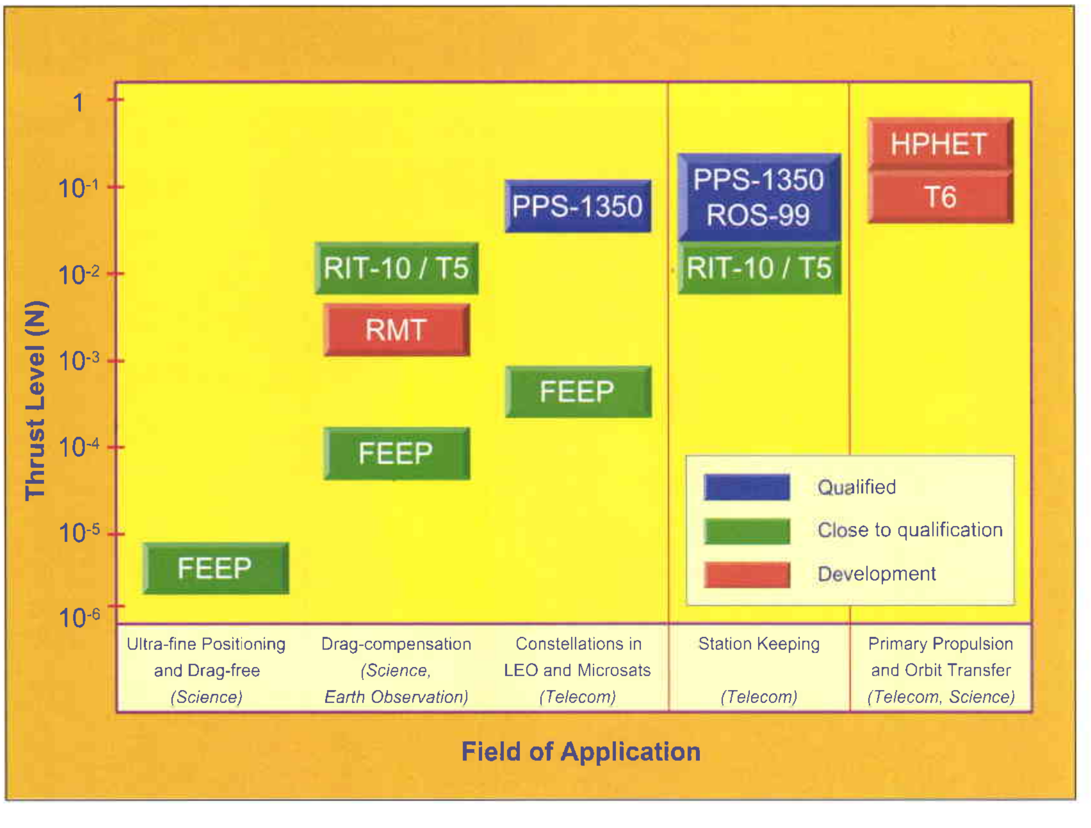


Figure 1. Fields of application for European Electric Propulsion systems

Electric propulsion for telecommunications satellites

The main areas of application for EP on European telecommunications satellites are as follows:

North-south station keeping for GEO telecommunications

In the last years, the trend in GEO telecommunications satellites has consolidated into a considerable increase in electrical power to satisfy the payload needs, an increase in platform size to accommodate the payload and longer mission durations of up to 15 years. As a consequence, the use of EP for North-South Station Keeping (NSSK), which is the first step in the operational use of EP for GEO telecommunications, is essential for efficient spacecraft propulsion and is now being adopted, at least as an option, by all of the World's major telecommunications satellite manufacturers.

In Europe, ESA will fly two RIT-10 (D) and two T5 (UK) gridded ion engines on its Artemis spacecraft (Fig. 2). Artemis (the Advanced Relay and Technology Mission Satellite) is being developed for testing and operating new telecommunications techniques. It is scheduled for launch in the year 2000 on a Japanese H2A launcher in the framework of a cooperation agreement with the Japanese space agency NASDA. Figure 3 shows the RIT-10 thruster undergoing qualification testing.

In the year 2000, the French Space Agency, CNES will fly PPS-1350 Hall-effect thrusters on its Stentor GEO experimental satellite. The PPS-1350 system is currently being developed jointly by SNECMA (F) and ETCA (B), working on the thruster (Fig. 4) and the power processing unit, respectively.

Another Hall-effect thruster with performance similar to the PPS-1350 is being developed and qualified by Matra Marconi Space (UK/F) in collaboration with the Keldish Research Institute in Russia. This thruster, called ROS-99, is currently undergoing a lifetime test in Russia.

Figure 2. The Artemis satellite and its ion thrusters

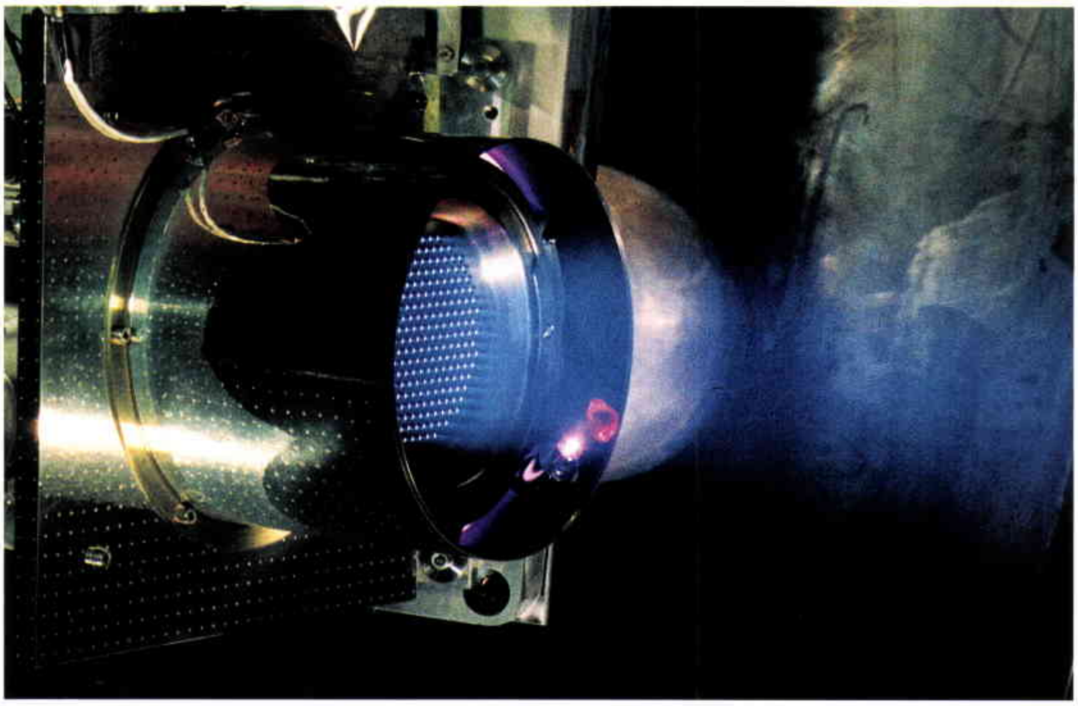


Figure 3. The RIT-10 Gridded Ion Thruster (courtesy of Daimler Chrysler Aerospace)

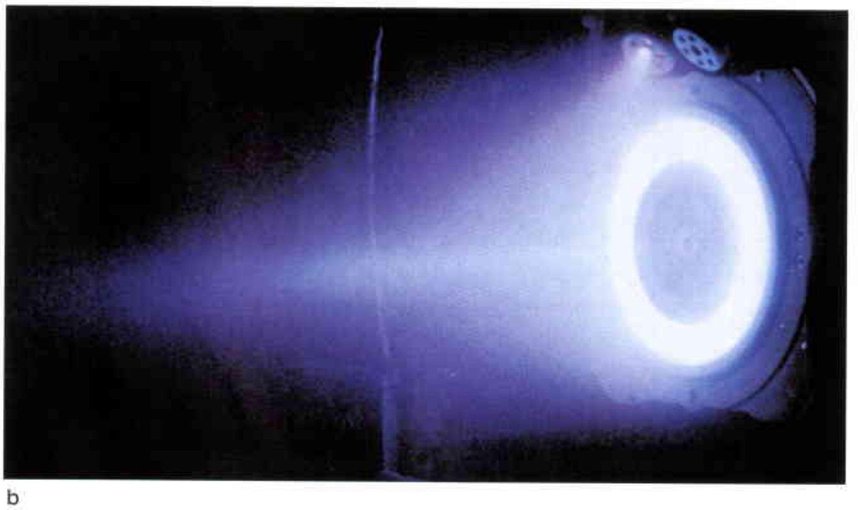
Under the pressure of international competition, the two major European telecommunications manufacturers, Matra Marconi Space and Alcatel, have initiated the development of a new generation of geostationary platforms, known as Eurostar 3000 and Spacebus 3000, respectively, which offer the option of using Hall-effect thrusters for NSSK operations. In 1997, Alcatel won a contract from Societé Européenne de Satellites of Luxembourg (SES) to build ASTRA 1K, which will be the first large operational European GEO satellite to offer the option of using Hall-effect thrusters for NSSK. ASTRA 1K will be launched at the end of 2000.

a

Optimal use of EP on future GEO telecommunications satellites for orbit-transfer and other operations

In a second step leading to optimal use of electrical propulsion on the next generation of GEO telecommunicatons satellites, EP operations can be extended to include functions other than NSSK, notably full or partial orbit transfer to the GEO orbit, east-west station keeping, momentum-wheel speed control and possibly other attitude-control functions and spacecraft de-orbiting at end of life (EOL). Matra Marconi Space and Alcatel are currently working on the development of a new generation of GEO platforms that will make optimum use of EP. Furthermore, Arianespace, the European organisation charged with the commercialisation of the Ariane family of launchers, expects the adoption of EP on future GEO telecommunications spacecraft, in particular for the orbit-transfer function, to have a major impact on the future requirements for the Ariane-5 launcher.

To prepare for the next generation of European GEO telecommunications satellites that will make optimum use of EP, ESA has initiated activities in the short and medium term in coordination with European industry, aiming at the timely definition and development of the EP system that will eventually be used on these new satellites. The most important of these activities will develop and qualify a new High-Power Hall-Effect Thruster (HPHET), in the 3 kW class. The contract for this activity has been awarded to Matra Marconi Space (UK/F) and its subcontractors, DERA (UK), Inasmet (E) and Centrospazio (I). This activity, co-funded by ESA and industry, will also include a lifetime qualification test to be performed in a new European large test facility for EP, being built in Italy by Centrospazio/ALTA. This activity was started in March 1999 and qualification of the new engine is expected in 2001.



b

Figure 4. The PPS-1350 Hall-Effect Thruster (courtesy of SNECMA)
a. A model of the thruster
b. The thruster undergoing a life qualification testing

EP for telecommunications constellations in LEO

Many satellite constellations are under study and development today which will adopt electric propulsion for part or all of their manoeuvres. The potential of this new market segment is enormous, due particularly to the possibility that EP offers to reduce the number of launchers needed to put a constellation into orbit. In Europe, activities for these types of applications have just begun, and European thrusters will be used on future satellite constellations for different operations. ESA considers it important that European industry takes advantage of the commonalities with the EP systems developments for application on GEO telecommunications or scientific satellites in order to make EP systems available for LEO constellations as soon as possible.

Matra Marconi Space is involved with Daimler Chrysler in the preparatory activities for the development of the platforms for Motorola's Teledesic and Iridium Plus telecommunications constellations, which will use electric propulsion

THRUSTER	CATEGORY	MANUFACTURER	STATUS
PPS-1350	Electrostatic (Hall-effect)	SEP (F)	Qualified for GEO spacecraft Station Keeping and LEO constellations.
ROS-99	Electrostatic (Hall-effect)	Matra Marconi Space (UK/F)	Qualified for GEO spacecraft Station Keeping.
HPHET	Electrostatic (Hall-effect)	Matra Marconi Space (UK/F)	Developed for obit transfer of new GEO and LEO constellations. Qualification in 2001.
RIT-10	Electrostatic (Gridded ion engine)	Daimler Chrysler Aerosp. (D)	Under qualification for GEO spacecraft Station Keeping (2000)
T5	Electrostatic (Gridded ion engine)	Matra Marconi Space (UK)	Under qualification for GEO spacecraft Station Keeping (2000)
T6	Electrostatic (Gridded ion engine)	DERA (UK)	Engineering model. Developed for new GEO spacecraft station keeping.
RMT	Electrostatic (Gridded ion engine)	Laben-Proel (I)	Engineering model.
RIT-15	Electrostatic (Gridded ion engine)	Daimler Chrysler Aerosp. (D)	Advanced breadboard.
ESA-XX	Electrostatic (Gridded ion engine)	Daimler Chrysler Aerosp. (D), AEA (UK)	Breadboard.
FEEP	Electrostatic (Field Emission)	Centrospazio (I)	System ready. Flight Qualification in 2000.
Indium LMIS	Electrostatic (Field Emission)	ARC (A)	Breadboard
Ammonia Arcjet	Electrothermal	IRS (D)	Qualified for Amsat P3-D
Hydrazine Arcjet	Electrothermal	FIAT-Avio (I)	Engineering model
MPD thrusters	Electromagnetic	Centrospazio (I), IRS (D)	Laboratory models

Table 1. Main European developments in Electric Propulsion

for orbit transfer and other functions on a total of more than 200 satellites. The HPHET mentioned above is a candidate for application on these constellations.

Furthermore, Alcatel is developing Skybridge, a satellite-based system designed to provide global access to interactive, multimedia communications. Built around a constellation of 80 LEO satellites, Skybridge provides the communications infrastructure for a full range of broadband services, including Internet access and high-speed data communications. The EP thrusters to be used on Skybridge are of the PPS-1350 thruster class.

Electric propulsion for scientific satellites

EP for primary propulsion of interplanetary missions

The use of electric propulsion for scientific spacecraft is recognised as an important step to enhancing missions, and projects are being proposed to validate in the short term the use of EP for interplanetary missions. For such missions, replacing or augmenting chemical propulsion with electric thrusters as the primary propulsion system can bring the following benefits:

- an increase in net payload mass (enabling missions to be conducted that would otherwise be impossible)
- a reduction in flight time with respect to mission based on chemical propulsion and complex gravity-assisted operations (reduction in mission operation costs)
- independence from launch-window constraints, which are imposed by the classical gravity-assisted planetary fly-by operations (allowing increased scientific objective for the missions)
- possibility to use small/medium launch vehicles (providing substantial launch-cost savings).

The specific mission requirements, in terms of power availability, satellite mass and mission profile, dictate the choice of the particular EP technology to be used.

As in the USA, in Europe too initiatives are already being taken to embark primary electric propulsion systems on scientific satellites. ESA is particularly active in this field and many new scientific missions being proposed by the Agency are based on the use of such systems.

The first of ESA's SMART missions (Small Missions for Advanced Research in Technology), SMART-1, is a small lunar orbiter devoted to the demonstration of innovative and key technologies for scientific deep-space missions. A highly innovative and low-budget mission to explore the moon, SMART-1 was formally approved by ESA's Delegations in 1999. The most important technology to be flown on the 350 kg spacecraft, scheduled for launch at the end of 2002 as an Ariane-5 auxiliary payload, will be solar electric propulsion. This will constitute its primary propulsion for escaping from the Earth's gravity, for its 17-month cruise to the Moon, and for staying in lunar orbit for six months. It will be the first time that Europe uses EP as the primary propulsion for a scientific satellite.

SMART-1 will therefore serve as test-bench for other missions using EP as far as the following functions are concerned:

- integration and testing of the electric propulsion system
- spacecraft commissioning phase
- spacecraft operations during transfer phases based on low-thrust trajectories and arcs
- spacecraft electrical power distribution in the presence of a power-demanding EP system
- spacecraft in-orbit control combining attitude and position data to thrust along the velocity vector
- low-thrust fly-by and planetary (i.e. Moon) capture
- low-thrust planetary observation mission and descent phase.

Figure 5 is an artist's impression of the SMART-1 spacecraft, being pushed by its electric-propulsion engine.

Due to the mass limitations on the spacecraft and the consequent limitations on the electrical power (1.4 kW available for the EP system at the beginning of life in orbit), the thruster to be used on SMART-1 is a scaled-down version of the thrusters that will eventually be used on future operational missions. The candidate thrusters for this mission were therefore the ones currently available for the station-keeping of GEO telecommunications satellites, in particular the PPS-1350 Hall-Effect Thruster and the RIT-10 and T5 gridded ion engines.

Figure 5. The SMART-1 satellite being pushed to the Moon by Electric Propulsion (artist's impression courtesy of Swedish Space Corporation)

The PPS-1350 thruster developed by SNECMA (F) has eventually been selected for the mission.

The SMART-1 project is now proceeding to the development phase and the spacecraft industrial prime contractor is Swedish Space Corporation (SSC). In the framework of the contractual agreement with SSC, the electric propulsion system for SMART-1 is being defined and procured by ESA as 'customer-furnished equipment' to the satellite prime contractor. A dedicated team in the ESA Directorate for Technical and Operational Support, at ESTEC (NL), is responsible for the procurement of the subsystem on behalf of the ESA SMART-1 project and the satellite prime contractor.

SMART-1 will be the precursor of new, challenging deep-space and interplanetary missions. Among missions of this type currently in preparation, the ESA's Horizon 2000 Plus scientific programme includes a Cornerstone mission to the planet Mercury. A mission to Mercury is inherently complex due to the high energy requirements and the hostile environmental conditions. For such a mission, electric-propulsion transfer phases offer significant mass-saving advantages compared to chemical propulsion, particularly if used in combination with gravity-assisted manoeuvres. An industrial feasibility study for a mission to Mercury based on the use of EP has been awarded by ESA to Alenia Aerospazio (I), with Dornier Satellitensysteme (D) as subcontractor. The current mission configuration is based on a 'cruiser' which will deploy an 'orbiter' close to Mercury, and possibly also a minisatellite and a small penetrator. The 'cruiser' and the 'orbiter' propulsion system will be based on gridded ion engines or Hall-effect thrusters. The study was completed in 1999 and has confirmed the feasibility of such a challenging mission, therefore opening the door to further technology assessment and, if the mission should indeed be selected, the development of the EP system itself.

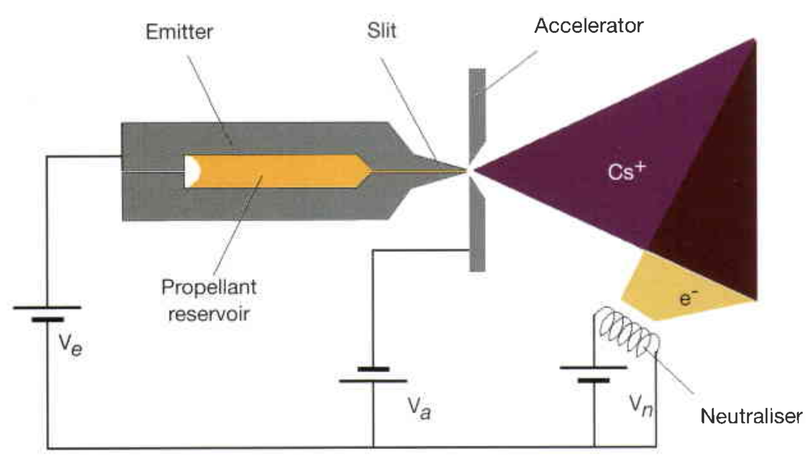


Figure 6. Working principle of a field-emission thruster

A similar use of EP has been assessed in the framework of two internal ESA studies for a Venus and a Mercury Sample-Return Mission. For these two missions also, EP is considered a prerequisite.

EP for fine-pointing and drag-free scientific spacecraft

The very low and highly controllable thrust levels provided by some electric propulsion technologies enable a new category of missions to be contemplated which would otherwise not be possible due to their demanding fine-pointing and positioning requirements. Some European electric-propulsion systems are especially suitable for missions requiring very low thrust levels with accurate control capabilities.

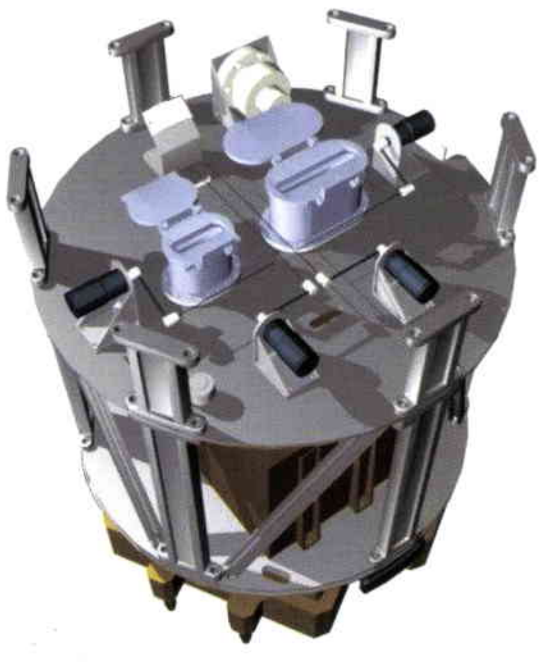
Field Emission Electric Propulsion (FEEP) thrusters make use of the field-emission principle to ionise and accelerate liquid metals such as caesium, rubidium or indium. A schematic of the working principle of a FEEP thruster (called an 'emitter') is shown in Figure 6. The thrust produced by such devices is very low (micro-newtons to milli-newtons), but the exit velocity of the ions is by far the highest among the space propulsion systems (up to 30 times the exit velocity of a conventional chemical propulsion engine). This implies such low propellant consumption that in most cases the propellant reservoir can be integrated into the thruster itself, representing a significant advantage over other propulsion systems that require separate reservoirs. This results in a very compact and light propulsion system that is easy to integrate on board the spacecraft. For all of these reasons and their inherent thrust characteristics, FEEP thrusters are perfectly suited for high-precision pointing missions and also for the attitude and orbit control of micro satellites (weighing a few hundred kilograms at launch). In particular, the application of FEEP is being investigated for the Italian microsatellite platform MITA (150 kg class), developed by Carlo Gavazzi Space, which will be used for scientific and commercial applications.

Development of a complete FEEP system at Centrospazio/ALTA (I) is being funded by ESA within the framework of an R&D programme, aiming at a flight demonstration of the system at the end of the year 2000 on a Shuttle Get-Away Special (GAS) facility. The FEEP GAS experiment assembly is shown in Figure 7, and the Centrospazio FEEP thruster, mounted in its protective container, in Figure 8.

A second field-emission thruster concept, derived from a space-charge compensator, is also being investigated at the Austrian Research Center (A).

With its FEEP system, Europe has a unique expertise in the field of low-thrust electric propulsion for applications requiring micro-newton to milli-newton thrust levels with high control capabilities. This expertise is also recognised outside Europe, where missions are also being proposed that will use this technology.

Probably the most challenging mission that foresees the use of FEEP thrusters is the Laser Interferometer Space Antenna (LISA), currently proposed in the framework of ESA's Horizon



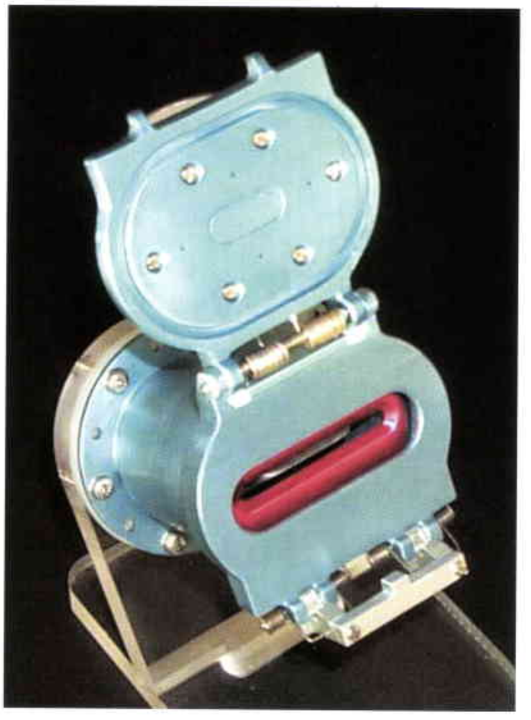


Figure 7. The FEEP flight experiment assembly on a Shuttle Get-Away Special

Figure 8. The FEEP thruster in its protective container (courtesy of Centrospazio)

2000 Plus Programme. The primary objective of the LISA mission is to detect and observe gravitational waves. The current mission concept, illustrated in Figure 9, consists of a cluster of spacecraft connected by laser beams, forming an equilateral triangle space interferometer. When a gravity wave passes through the system, it causes a strain distortion of space, which will be detected by measuring the fluctuations in separation between proof masses inside the spacecraft. The success of the mission depends on the high performance of such a sophisticated accelerometer concept, which must work under drag-free conditions, which means in turn that the external perturbation applied by the external environment to the spacecraft must be shielded. The drag-free control of the spacecraft will be provided by FEEP thrusters, operating at micro-newton thrust levels.

Still based on a space Interfereometer configuration, the InfraRed Space Interferometry Mission (IRSI-DARWIN or DARWIN for short) is another Cornerstone mission candidate in the ESA Horizon 2000 Plus science plan. The goals for this mission is to detect terrestial planets in orbit around stars other than our Sun for the first time, and to allow high-spatial-resolution imaging, also for the first time. A mission feasibility study has been performed by Alcatel Space and the resulting IRSI-DARWIN mission concept is presented in Figure 10.

A constellation of spacecraft forming the interferometer will rely on electric propulsion to perform orbit and attitude control and reconfiguration of the cluster of satellites. In particular, FEEP thrusters might be used to perform attitude and orbit control, orbit phasing and distance control. Collaboration and joint

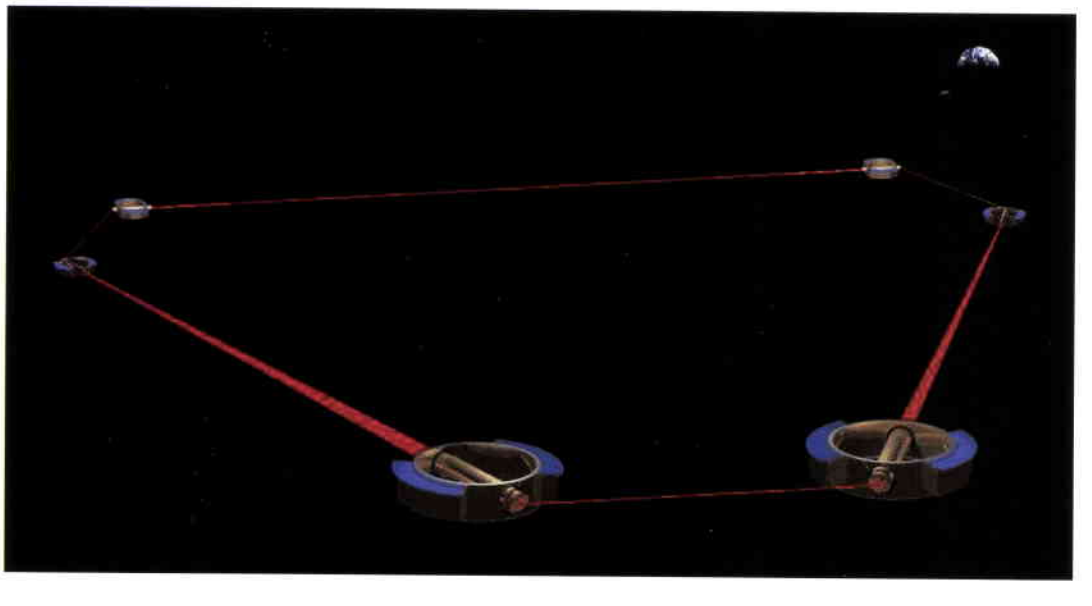


Figure 9. The LISA mission concept

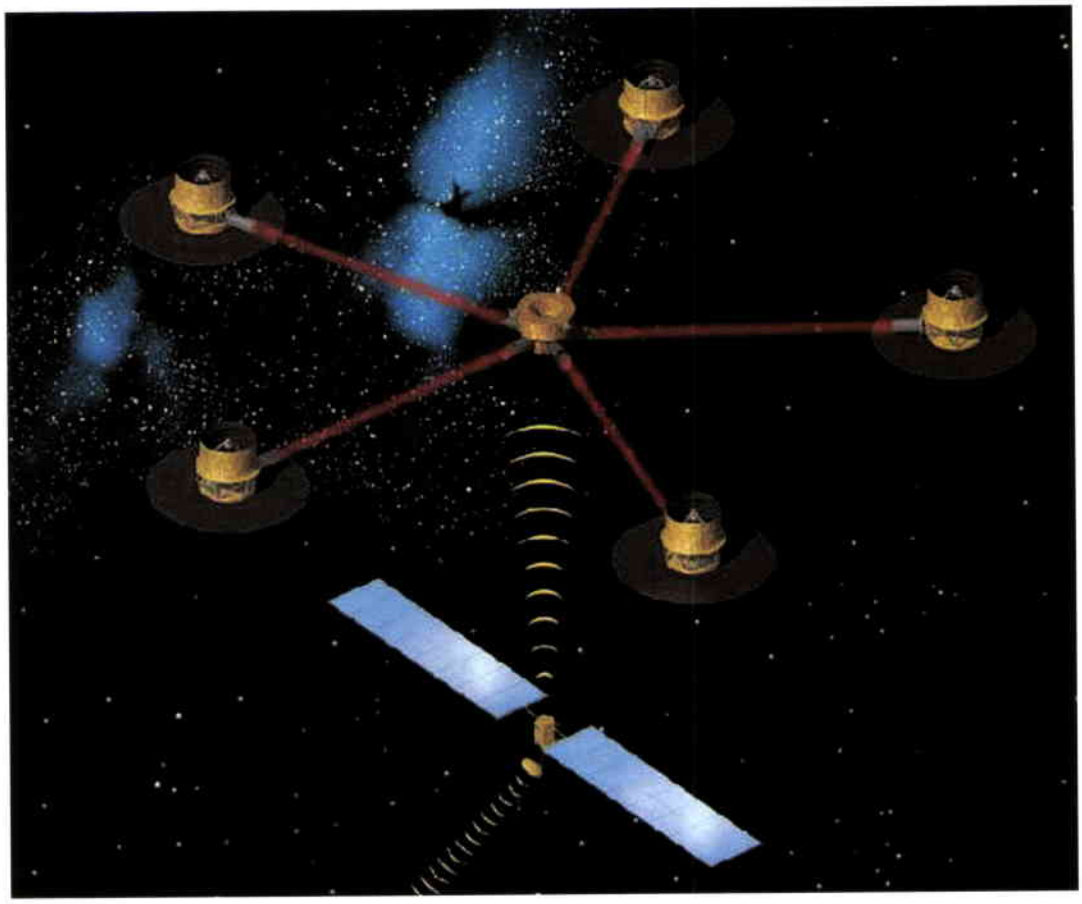


Figure10. The IRSI-DARWIN mission concept (courtesy of Alcatel)

demonstration opportunities for the DARWIN concept are currently being investigated by ESA and the USA.

Another important ESA mission requiring FEEP is GAIA, an advanced astrometric mission that is also proposed as a Cornerstone mission within the ESA Horizon 2000 Plus science plan. The GAIA mission's main objective is to perform a global astrometric survey of the whole sky with unprecedented accuracy (2-3 orders of magnitude more accurate than the successful ESA Hipparcos satellite, and five orders of magnitude more accurate than ground observations). Such performance will make possible a star catalogue 10 000 times larger than Hipparcos, with the observation of 1% of the total number of stars in our Galaxy. FEEP thrusters, operating this time at milli-newton levels, are currently baselined as actuators for the attitude and orbit control system of the GAIA spacecraft.

The use of electric propulsion is also foreseen for a new ESA mission called XEUS, which is a potential follow-on to the recently launched X-Ray Multi-Mirror spectroscopy mission (XMM). XEUS is under study with the endorsement of the ESA Horizons 2000 Survey Committee, who recommended 'analysing the potential offered by major high-energy astrophysics facility within the Space Station Utilisation Programme'.

XEUS would be a permanent X-ray observatory in space providing a telescope aperture equivalent to the largest ground-based optical telescopes. It consists of two separate spacecraft launched into Low Earth Orbit by a single Ariane-5. The mirror spacecraft (MSC) would be a slowly spinning spacecraft containing the X-ray mirrors, their baffles, two docking ports, and an attitude control system. The detector spacecraft (DSC) would contain the focal-plane instrumentation, coolers, a single docking port, and an attitude and orbit control system based on Hall-effect thrusters, capable of providing an alignment accuracy of better than one cubic millimetre with respect to the MSC. The DSC concept is shown in Figure 11. The two spacecraft would deploy following launch and maintain a separation of 50 m, corresponding to the focal length of the mirrors.

By making use of the ISS for refurbishment and by ensuring a significant growth and evolution potential in its design, XEUS would remain at the forefront of high-energy astrophysics research for more than 20 years.

EP for "Earth Explorer" Missions

Earth Explorer Missions are ESA research/demonstration missions for the post-2000 time frame that have been investigated within the framework of the Earth Observation Preparatory Programme (EOPP), with the emphasis on advancing the understanding of the different processes that help govern the Earth system. Electric propulsion is currently being considered as a key enabler for some of these missions, to perform tasks sometimes somewhat different from those on conventional telecommunications spacecraft, for instance as actuators in sophisticated control systems (precise thrust control), for drag compensation for orbit maintenance and to enable a drag-free environment. Due to the different requirements imposed by these missions on electric thrusters compared with their more conventional applications, assessments of existing European electric propulsion technologies (thrusters and peripherals) are currently being performed to identify the best candidates for these applications.

The first European Earth Observation mission based on the use of electric propulsion and selected for development is the Gravity and Ocean Circulation Explorer (GOCE) mission. GOCE is designed to measure the Earth's gravitational field with high accuracy. This mission is unique in that it aims at the sustained operation of a complex spacecraft at an altitude where re-entry would normally be expected within a very short period of time. At this altitude, between 250 and 300 km, the residual air drag will be very significant, and therefore a continuous thrust must be applied along the velocity vector to counteract this drag and to establish a drag-free environment on the spacecraft.

Electric propulsion is essential to the GOCE drag-free control. Its utilisation for orbit maintenance instead of conventional hydrazine allows one to save hundreds of kilograms of propellant and eliminates the sloshing. In addition, its utilisation for drag compensation allows one to counter also the low-frequency terms of the drag, thereby increasing the overall performance.

The low-thrust technology (up to 10 mN) that is being considered for GOCE is electrostatic propulsion, specifically the gridded ion-engine concepts currently under development or qualification in Europe. The engines most suitable for this application are the RIT-10 and the T5 as developed for Artemis (mentioned earlier), but with new electronics, and another low-thrust ion engine called RMT, being developed in Italy by Laben/Proel Tecnologie.

Ion thrusters will be used on GOCE in a new way, and this will require specific development work. Ion thrusters have been developed to provide maximum thrust in an intermittent fashion. In the case of GOCE, it will be necessary to modulate the thrust so that it exactly matches the aerodynamic drag. On-going investigations have already verified the basic suitability of the existing European ion thrusters for operating in the modulation regime demanded by GOCE.

FEEP thrusters are also being considered for the secondary propulsion system on GOCE.

Conclusion

Space agencies, satellite prime contractors and equipment manufacturers in Europe have already identified electric propulsion as a key technology for the future of space missions. As a result, it is being treated as top-priority technology item.

Many aspects of electric-propulsion technology still need to be mastered and the European effort in the coming years will concentrate on these areas. In particular, the establishment of a European capability in the area of EP system components will be pursued, together with the procurement of facilities for the production and ground qualification of EP thrusters and the provision of flight opportunities for their space validation. esa

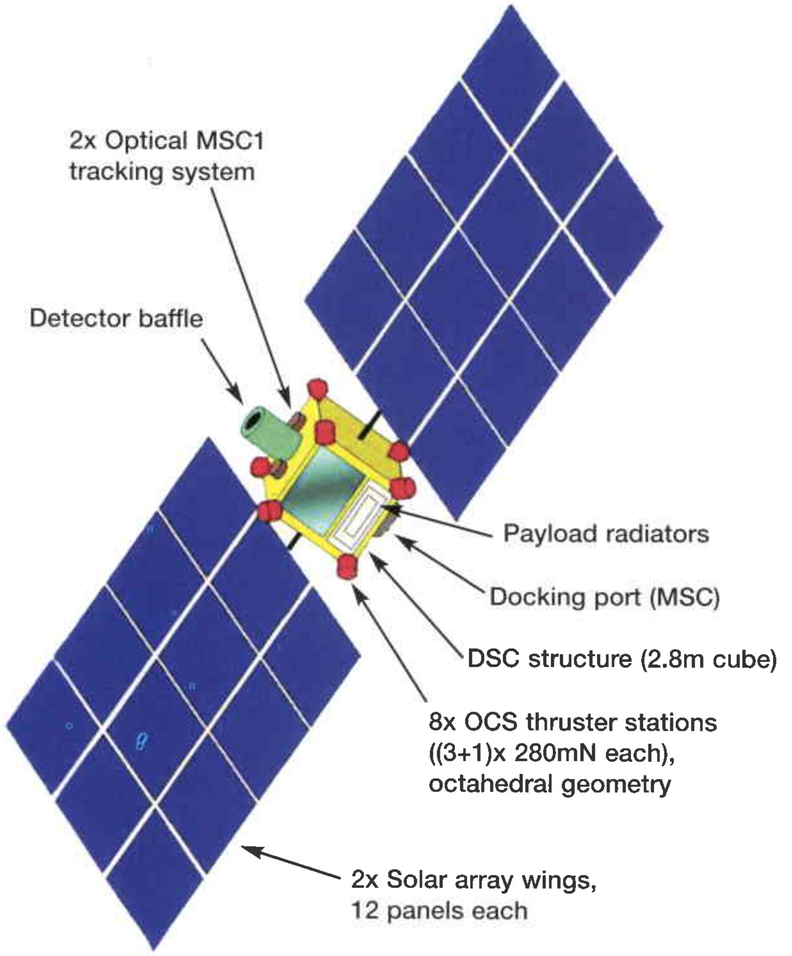


Figure 11. The XEUS Detector spacecraft concept

Road-Traffic Monitoring by Satellite

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In modern industrialised societies, there are large and escalating quantities of traffic on the roads. People are becoming increasingly environmentally aware and there are concerns that this volume of traffic is damaging people's health, our cities and the countryside, as well as using resources in a wasteful and irresponsible manner.

All off this is leading towards proposals, being discussed in many countries, for road-raffic management. In most countries road traffic is virtually unmanaged, with only minor indirect control being exercised over road vehicles. ESA has proposed an innovative system for road-traffic monitoring by means of satellite communications. A Web-based simulation environment provides a comprehensive and state-of-the-art framework for examining the performance of the proposed system, as well as a comprehensive analysis of the results produced.

Introduction

In any traffic management system, the provision of up-to-date, accurate and detailed quantitative information on traffic movement is likely to be a prerequisite for a successful system. This is not to underestimate the difficulty and cost of providing such information – buried inductive loops, roadside detectors, video cameras, etc. have all been tried with varying degrees of success. Such systems provide spot checks on traffic flow and possibly speed, but fail to provide a continuous indication of the movement of an individual vehicle through a traffic system. The cost of the infrastructure tends to limit its applicability to very intensively used road segments.

ESA has suggested an innovative system, based on fitting individual vehicles with GNSS position determination in combination with a low-cost satellite communications system. The proposed system is based on an existing ESA development that operates in the L-band (1.5 – 1.6 GHz) for the link between the mobile and the satellite. It uses a simple omni-directional antenna on the vehicle.

Clearly, for an accurate picture of the traffic flow to be built up, a large number of vehicles will need to be interrogated on a more or less continuous basis. This raises the problem of whether the satellite-based system would be able to handle the flow of data from the vehicles in a cost-effective manner.

In addition, it seems unlikely that, in the short or medium term, every vehicle would ever be fitted with such a system. The ESA proposal makes use of 'tracer vehicles', a concept that has been contemplated in several traffic-monitoring schemes. Only a small percentage of vehicles are equipped for providing their position, speed, etc. The assumption made is that these tracers provide sufficient information to derive a good picture of the traffic situation.

In order to evaluate quantitatively the expected performance of the proposed system, Aberdeen University has developed a Web-based simulation environment. This utilises a conventional simulation 'core' written in the general-purpose simulation language Simula, coupled via E/SQL extensions to a relational database. This database can be accessed from a commercial Unix 'Office' package that contains a Java applet that makes the simulation results available over the Web, using a conventional Web browser. Additionally, the applet makes it possible to edit the simulation configuration files via a Windows-style Graphical User Interface (GUI), as well as initiate simulation runs remotely. This enables remote users, such as National Traffic Authorities, to access and utilise the simulation tools using only their desktop PCs.

This facility has been used to promote the use of the proposed Road-Traffic Management (RTM) system with such interested parties. This is because it allows demonstrations of the system to be given at their premises, either via the Internet if they have access via their desktop PC, or via a GSM telephone linked to a laptop computer. Since the Java-applet-based simulator creates the graphics directly at the client-end of the link, even the limited bandwidth of the GSM data service allows realistic and compelling demonstrations of the proposed service to be given to interested parties almost anywhere and with the minimum of local infrastructure.

As well as evaluating the performance of the proposed RTM system quantitatively, the simulator has been used to validate the protocols through a comprehensive and detailed examination of the state transitions within the protocol state machine.

Traffic-management concepts

Proposals are currently being discussed in many countries for road-traffic management. In most countries, road traffic is virtually unmanaged, with only minor indirect control being exercised over road vehicles. This is surprising considering the volume of traffic, the restricted environment and the intense interaction between the vehicles. Although road vehicles are generally more manoeuvrable than trains and aircraft, one could not imagine such a lack of management at major airports, in crowded airways or along stretches of rail track such as we allow on our roads.

Over the years, a number of schemes have been tried to improve the flow of traffic in city centres or on major roads. It has long been felt that the existing road network, by virtue of being unmanaged, is inefficiently utilised and might better accommodate the traffic load placed on it. This would reduce the environmental impact by reducing the need for new roads and would reduce the times that road vehicles spend in traffic – often operating at their least efficient and most polluting.

In addition, one should not forget the improved economic efficiency that would result from a reduction in journey times and fuel consumption, as well as the reduction in accidents and the improvement in quality of life.

The traffic-management schemes that have been attempted have typically met with limited success. The suggested reasons for this are as diverse as the schemes themselves but one factor seems common amongst all the schemes surveyed – the lack of adequate and accurate traffic information. It seems entirely logical to suggest that one cannot hope to manage a system without understanding the behaviour of that system and having up to date and accurate measurements of its behaviour. In any closed-loop control system one needs to have a measure of the behaviour of the object being controlled.

The mix of traffic too can be important, with coaches, buses, cars and lorries all reacting differently to the road conditions.

For some time, there have been proposals to fit cars with sensors that might be interrogated by roadside units – but the cost of the supporting terrestrial infrastructure probably confines the applicability of such systems to limited, intense-traffic road segments.

Road-traffic monitoring by satellite

One of the key features of satellite communications is that a single satellite can cover a very large geographical area, making it feasible to dynamically allocate the communications resources where they are most needed at any given time. The scheme described is based on the ESA's 'Prodat' system. 'Prodat' is a system for satellite communication between small mobile terminals fitted in vehicles and fixed earth stations.

Prodat operates through the EMS payload of the Italsat-2 satellite. It uses the L-band (1.5 - 1.6 GHz) for the link between the satellite and the mobile station. The link between the Earth station and the satellite is in the Ku-band (11 – 14 GHz). The use of the L-band for the mobile link makes it possible to use small, omni-directional antennas on the vehicles. The use of the Ku-band for the feeder link makes it possible to access the satellite from fairly small VSAT stations (typically a 2 m dish), allowing one to install the stations directly at the user's premises. While roadside systems and in-road sensors mainly supply traffic-flow information, the proposed RTM system provides information collected from the individual vehicles, such as (GPS) position, speed and direction of travel, as well as historical information such as distance travelled in a given time period. Furthermore, it is possible to follow individual vehicles over extended time periods.

The RTM vehicle equipment can be economically combined with personal communication, for example for fleet-management applications, using essentially the same equipment, but on a separate communication channel.

RTM overview

The proposed RTM system is 'cell-based'. It allows the user, typically a road-traffic authority, to specify a number of geographically defined cells and to instruct the system to monitor the position, velocity, etc. of those suitably equipped mobiles that are in the geographical region defined by the cells.

In the RTM system, mobiles are fitted with a GNSS receiver, a Prodat satellite communications module, and a small micro-controller to coordinate activities. We considered that acceptance of any traffic-monitoring scheme would be dependent upon guaranteeing the anonymity of the participating vehicles. Yet this is to some extent in contradiction with the proposal that individual vehicles can be 'traced' through a section of road in order to determine the transit time. A solution to this dilemma is to make use of randomly selected, short-lived, vehicle identifiers assigned for the time period during which a vehicle is being continuously followed.

Communicating with a mobile in the proposed RTM system is a two-stage process. The first stage consists of making contact with equipped mobiles in the cells of interest. Mobiles are invited to respond to a 'random mode' poll if they are in the cell(s) specified in the poll. Each responding mobile picks a random temporary ID, which is used by the protocol to allocate to it another, system-unique random ID that it keeps as long as it is being followed. In order to cope with the case when the number of potential respondents exceeds the capacity of the communication system, an adjustable 'derating factor' tells the mobiles to respond to only a fraction of the random mode polls to that cell.

In the second stage, this second ID is used for regularly polling the mobile in 'addressed mode'. The mobile is followed, possibly across several cells, as long as it is in an area of interest, then dropped from the system. When a mobile is dropped, its ID is erased, so even a history analysis cannot establish the real identity of a given mobile. Since the ID is no longer in use, it may be re-used for another mobile.

The RTM simulator

The RTM simulator is a Web-based simulation environment that provides a comprehensive and state-of-the-art framework for examining the capabilities of the proposed system. It enables ESA to undertake comprehensive simulations of the RTM environment in order to obtain a detailed quantitative understanding of the system's performance and to demonstrate it to prospective interested parties. The basic simulation package is written in the object-oriented general simulation programming language Simula.

Although Simula is considered by some as a relatively old simulation language, it does have several important advantages over some of the more 'modern' graphical style approaches to simulation. In particular, in this application, the problem of multiple instantiation is a serious issue. The simulation runs being undertaken often contain several thousand 'mobiles' and

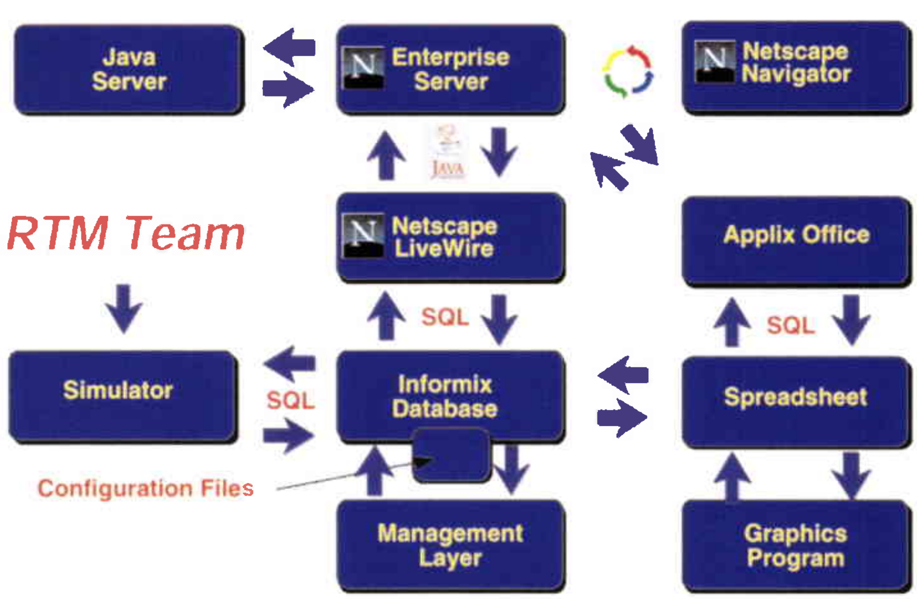


Figure 1. The simulation architecture

we were primarily concerned with efficiency of program execution and not with graphical user interfaces. A previous study carried out for ESA by Aberdeen University had conclusively demonstrated that Simula is computationally very efficient in such environments.

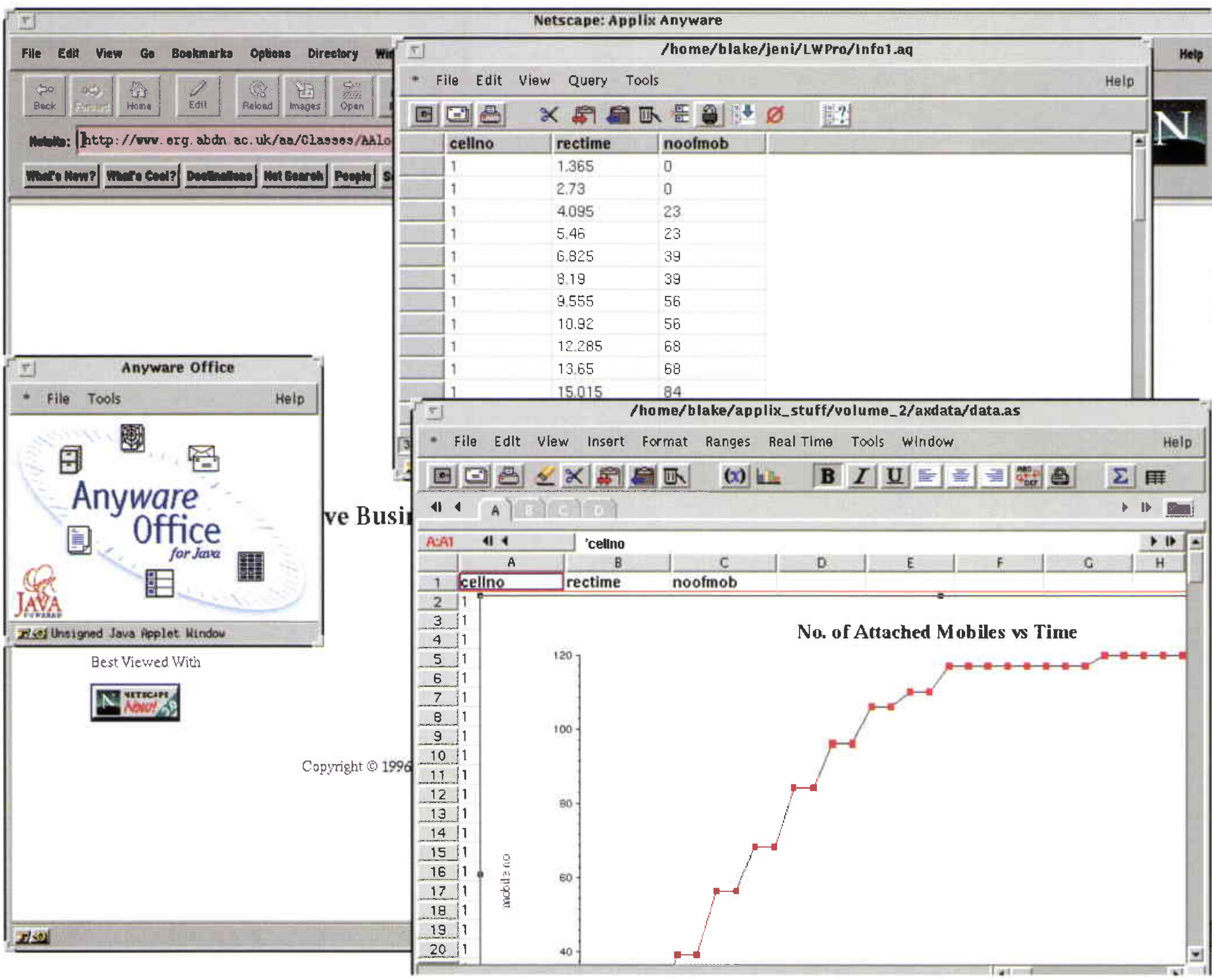
The overall simulation architecture is shown in Figure 1, while a typical 'screen shot' from the simulator is presented in Figure 2.

This simulator is linked to an Informix relational database for its input and output. Communication between the simulation program and the database is handled by embedded SQL (Structured Query Language) extensions. SQL is a standard way of communicating with relational databases. Both the simulation program and the database are controlled by Netscape's LiveWire application manager, which allows applications running on a remote machine to be controlled via the Internet and the World Wide Web (WWW) via a normal Web browser.

In addition, the simulation environment uses Applix Corporation's 'Office' package and their 'Anyware' Java server. This package allows the Applix software to use embedded SQL extensions to retrieve the data from the Informix relational database for processing, using the Applix Spreadsheet application which has a macro programming language capability for results processing. The processed results are then transferred to the Applix Graphics application for display. By using the Applix Anyware Java server, the results of the simulation are made available on a remote machine (client) using a regular (Java enabled) Web browser, such as Netscape Navigator or Microsoft Internet Explorer. The advantages of this approach are that remote users (such as national traffic authorities) are able to access and use the simulator remotely by means of a Web browser only. The simulator's host computer handles the heavy computational load.

However, by using the Java browser, the user does not need to download graphics files from the simulator for display at the user's PC. This approach would have the associated problems of slow downloading due to the large graphics file size and Internet bandwidth limitations (bearing in mind, too, that the results from the

Figure 2. A typical simulation session screen



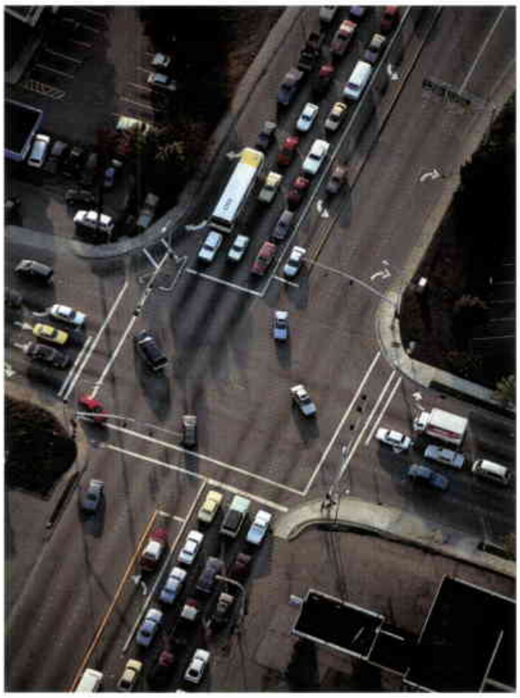
simulator can be displayed in real time). Instead only the data to be plotted are downloaded; the detailed graphics display is produced locally by means of the Java applet.

Web-based simulation strategy
There is much current interest in undertaking simulations on the Web and the authors have collected a substantial volume of material relating to this activity. Nevertheless, we believe that the system being used here is innovative in a number of respects, as discussed below.

One of the clearest advantages of using Web-based simulation is platform independence, in that users need only to have access to a commonly available Web browser (usually freely available) and an Internet connection to be able to gain access to the simulation environment. The authors of the simulation package are relieved of the task of having to provide versions of their simulator for a range of different computing platforms and operating systems. In addition, the graphical interface to the user provided by the Web browser for accessing the simulator is now 'maintained' by a third party (Netscape or Microsoft, for instance), relieving the simulation author of this task too. The simulation is run on the Web server's computing platform and is now much more under control, preventing unauthorised modifications and copies of the software from being made.

Running simulations over the Internet is often seen as being disadvantaged by the relatively poor bandwidth of the Internet. This typically means that graphics generated by a simulation program can take a substantial period of time to download. In the approach taken by the authors, however, a Java server is integrated with the simulation package. This server downloads (once only) a Java applet to the user's Web browser that gives the user a 'window' into the simulation environment at the server. Graphics that are provided to the user are generated locally at the client end of the link, with only the raw data being transferred over the network. This very substantially improves the (perceived) performance from the user's perspective.

Development of the traffic model
Early traffic models employed in the RTM simulator were a simplistic representation of a 'real world' traffic environment and were intended to be used merely as a means of verifying the behaviour of the RTM protocol. By that, we mean that it was not intended to be particularly quantitatively accurate, rather it provided a deterministic model that could be used to perform repeatable experiments with the RTM system. Communications engineers find it useful to use simplified data traffic models (say, exponential rate of arrival) to test and compare the performance of different protocols, or to experiment with changes in the protocol, or to provoke repeatable error conditions. The RTM group used a similar approach for work on the RTM system. A simplified deterministic traffic environment was established in the simulator and was used to test and 'validate' the behaviour of the protocols.



At the start of the project, it was proposed that either a commercial or academic traffic simulator be used, rather than a bespoke one. The reason for this was that it was felt that a proprietary traffic simulator would have little credibility with potential RTM customers and would consume effort that could be more effectively and profitably used elsewhere. However, for a variety of reasons, none of the existing simulators were suitable for use by the RTM software. This was because these simulators fall into two categories, namely microscopic and macroscopic. Microscopic simulators – such as Edinburgh University's 'Paramics' – are designed to provide a very detailed simulation of short-range traffic interactions. Such simulations might include the interaction between vehicles at traffic intersections, for example. Several commercial microscopic simulators exist that are sold to traffic and road authorities to help in the design of new traffic schemes. For example, Aberdeen City's Traffic Authority has a simulator that can be used to pose 'What if' questions, such as the effect of changing the width of traffic lanes at an intersection.

Macroscopic simulators are typically 'flow-based' in that they do not consider individual vehicles, but are rather concerned with the number of vehicles passing a point. Such simulators are used to provide estimates of traffic volumes to help in road planning.

The RTM Traffic Model

The objective of the RTM Traffic model is to provide a credible model that can be used to evaluate the performance of the RTM system as a whole. Such a model needs to be able to provide position and speed information on the individual vehicles it is simulating. This contrasts with flow-based models that indicate only the number of vehicles per hour that pass a certain location within the model. Such a traffic model has no concept of an individual vehicle and has no way to locate such vehicles.

Our model is based on the Netsim Traffic Simulator in widespread use by many traffic authorities. Netsim, which is freely available for both PC and Unix platforms, is intended to be used by the traffic engineer and researcher as an operational tool for the purpose of evaluating alternate traffic control and traffic management strategies. It has the core facilities needed to serve as a foundation for our model, and lends itself to easy extension with the additional properties that we need. The input data requirements are rather extensive and include network supply features, traffic demand patterns and signal timing. The network is made up of directional links and nodes and the physical features of each link must be specified. The traffic demands are entered as input and output network flows with specified traffic composition. A Netsim pre-processor simplifies the process of preparing and checking the input data. It includes a comprehensive set of automatic 'diagnostic checks', which are performed on all data inputs. It also provides for the convenient packaging of successive runs based on the sequential modification of input conditions. The Netsim post-processor consists of a set of data-manipulation routines that are designed to operate on successive outputs from the main simulation program. It can compare such runs and build a historical data file summarising the results. We have made some changes to the program to provide us with positional information on each of the vehicles in the model.

We were fortunate to have access to a substantial database of vehicle flow measurements made by a national road research laboratory. These measurements included vehicle velocity as measured by spaced (buried loop) transducers. We used these data as input to Netsim. This provided us with a simulation model of the road for which we have actual measurements under a wide variety of conditions. We constructed this model and tested it under a variety of conditions by comparing the actual measured traffic data with that predicted by the model. The fit was remarkably good under most conditions.

This model was used as the basis for the RTM Traffic Model. We were able to run this traffic model under a variety of conditions with the 'road model' representing the road for which we have actual measurements. As a consequence, we can use the RTM simulator to 'monitor' the vehicle characteristics under a variety of different conditions and then compare the results obtained with those actually measured. We believe that this approach provides an improved level of confidence in the performance of the RTM system.

We have consulted the traffic engineers at the road research laboratory in order to understand the differences between contrasting traffic conditions and how these conditions are recognised or categorised. We need to understand the conditions that such traffic engineers are interested in, and whether we can recognise them from our RTM model.

We have compiled a portfolio of traffic statistics that we have used to evaluate the performance of the proposed RTM system. We now believe that the traffic model we have is sufficiently representative under carefully controlled conditions to be able to provide credible quantitative evidence of the system's performance.

We need to understand the number of equipped vehicles (tracers) needed to provide statistically significant information on the behaviour of the traffic. This activity only becomes credible if one has access to a credible traffic model. We have generated several different test traffic scenarios that have been identified by the road research laboratory. Each of these scenarios can be identified from the buried-loop data provided by them – as well as visual observations made available to us. We use these data as input to Netsim. We then use the traffic model as the input to the RTM simulator. From the RTM simulator, we gather data on the behaviour of the tracer vehicles. We then correlate the behaviour of the tracer vehicles with the average behaviour of the vehicles observed from the buried loops or from our traffic model.

Using the RTM simulator, we have been able to determine the percentage equipped vehicles required to provide a consistent 95% confidence limit, in terms of the correlation between the behaviour of the 'tracers' and the vehicles as a whole, across a variety of traffic authority 'recognised' scenarios. To achieve an acceptable 95% confidence limit on our measurements, the poll interval that we need will be dependent on the 'scenario' in the cells. This poll interval will set an upper limit to the capacity of our system – the total number of cells, mobiles, etc. that we are able to monitor and still achieve an acceptable level of confidence in the results. We are now able to understand this relationship by being able to operate the RTM system with a parameterised model derived from actual measurements made by the road research laboratory.

Road research laboratory data

The data provided by the road research laboratory consist of flow-based measurements from a number of motorways and urban areas. For the RTM work, we used only those results for which observational data were available:

- Rural motorway: 300 data sets
- Urban motorway: 101 data sets
- A variety of major roads (not motorways) - 135 data sets
- Miscellaneous
- Traffic flow through roadworks (35 data sets)
- Accident observations (5 data sets)
- Effects of breakdowns (8 data sets)
- Other obstructions (9 data sets).

For the motorway data, the traffic conditions were classified by the observers into a variety of categories, from free-flowing to completely stopped. Examples were:

- 'Free flowing'
- 'Low volume' through to 'free flowing, heavy volume'
- 'Stop-and-go'
- 'Completely stopped for more than five minutes'.

For each of these conditions, flow-based data were available and were used as input to Netsim. The traffic model was then run to reproduce the flow data as a 'cross check' on the accuracy of the resulting model. The RTM simulator was then run with varying percentages of 'tracer vehicles' and the RTM system's ability to correctly identify the resulting traffic scenario measured (for each of the scenarios, the road research laboratory has defined guidelines for the observers to correctly identify them).

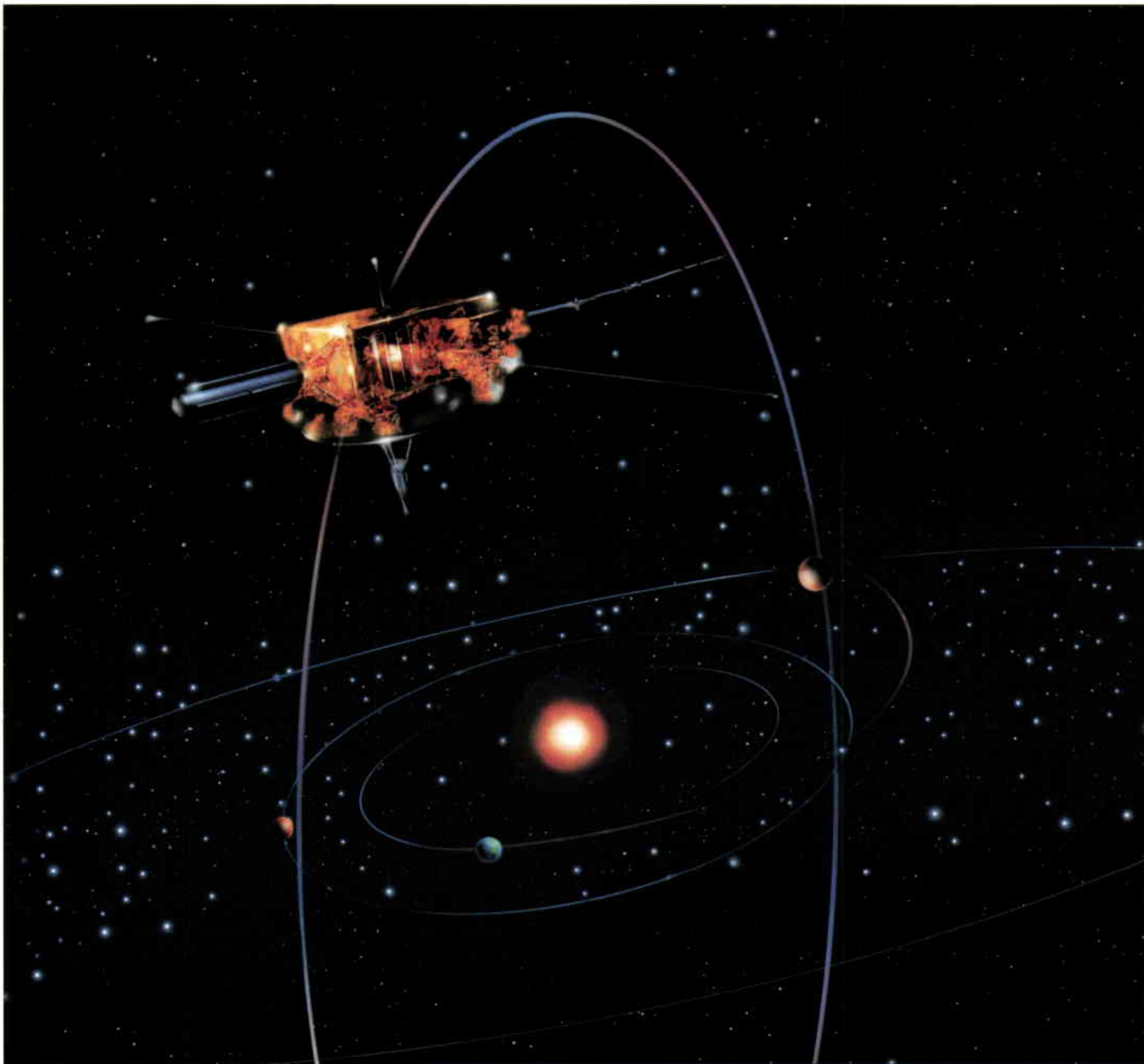
Results from the RTM Traffic Model

As might be expected, when the variability of traffic behaviour is small, only a relatively small percentage of tracer vehicles is required. When the traffic behaviour is 'chaotic', a significantly higher percentage of tracer vehicles is needed. For the nearly 700 data sets for which observations were available, the Netsim traffic model was parameterised and used in conjunction with the RTM simulator to determine the percentage of tracer vehicles needed to achieve a 95% confidence limit in correctly identifying the traffic conditions as reported by the observers. Typical percentages vary from under 1% (stopped traffic) up to 10% (urban traffic). The percentage of tracer vehicles also affects the time that the RTM system takes to correctly report a particular condition. This will be of importance for quickly identifying conditions such as traffic jams, accidents, etc. For the previously reported results, an acceptable 'reporting time' of 300 seconds was assumed. Since the RTM system 'polls' mobiles one-by-one and has a limited bandwidth, the total number of vehicles 'attached' to the RTM system is also an important parameter. If more vehicles are polled, then each individual vehicle will be polled less frequently and the reporting time will be adversely affected.

Conclusion

We have described the development of the protocols for an ESA-proposed satellite-based Road Traffic Monitoring system. The innovative Web-based simulation environment constructed has certainly been of considerable help in understanding the behaviour of the protocols, as well as providing quantitative information on the expected performance of proposed system. The traffic model based on the Netsim simulator has allowed us to relate flow-based measurements taken from buried inductive-loop sensors to the RTM measurements. This in turn has enabled us to understand the performance of the RTM system, and in particular to predict the number of equipped mobiles needed to provide a reliable (95% confidence limit) estimate of the traffic conditions.

This ESA-funded study has shown that the proposed satellite-based RTM system is a viable and economic approach to monitoring road traffic. As a result, the Agency has instigated a pilot study that will investigate the RTM application further, using ESA's existing Prodat system and real vehicles. esa



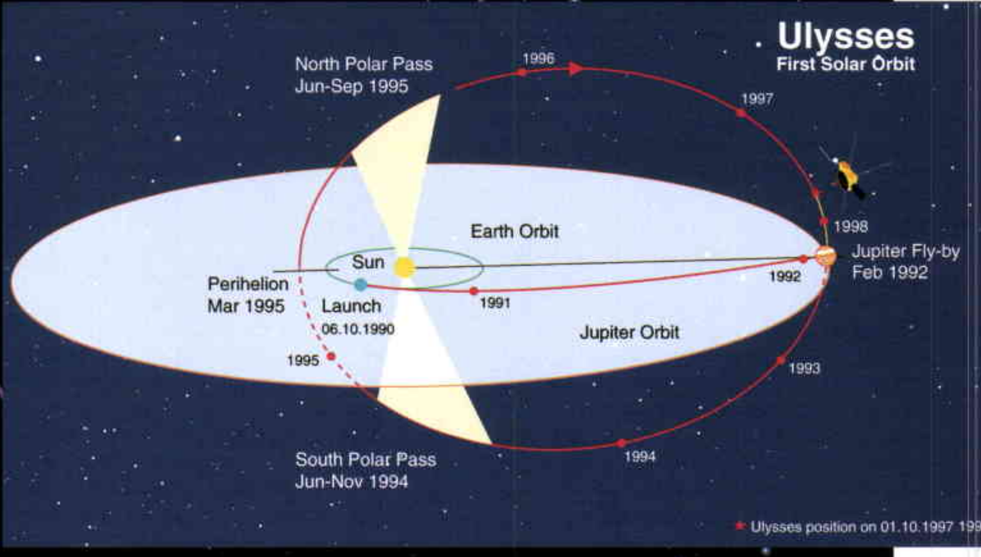


Figure 1. The first orbit of Ulysses around the Sun. The path of the spacecraft is shown in red. The red dots indicate the position of Ulysses at the beginning of each year. The Jupiter fly-by swung Ulysses out of the ecliptic (the plane in which the planets orbit) and into a solar polar orbit. Also shown are the solar passes in 1994 and 1995. The Ulysses orbit is viewed from a perspective of 15° above the ecliptic plane

Figure 2. The second orbit of Ulysses around the Sun in April 1998, when the spacecraft reached aphelion (its farthest distance from the Sun). The aphelion position also corresponds to the distance of Jupiter's orbit. Note that the spacecraft's orbital period is 6.2 years, compared to 11.9 years for Jupiter

The Ulysses Solar Minimum Mission CD-ROM Archive

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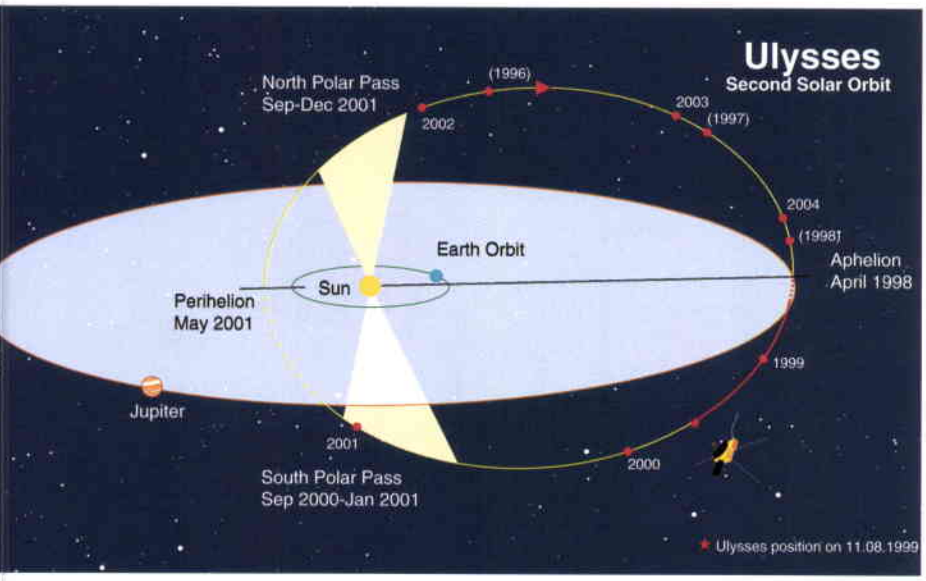
On 30 September 1995, Ulysses completed the primary phase of its mission, becoming the first spacecraft to chart the high-latitude regions of the heliosphere. The spacecraft's scientific payload returned unique and continuous data throughout this so-called Solar Minimum Mission, covering the in-ecliptic transfer to Jupiter and its flyby, the descent to the south pole of the Sun, the rapid transit from the southern to the northern hemisphere, and the passage over the north pole. Currently, Ulysses is making its second solar orbit during a time of increased solar activity, in contrast to the relatively quiet solar minimum conditions experienced during the first orbit.

The data collected by the many experiments flown on Ulysses during the Solar Minimum Mission are now available as ESA Special Publication SP-1230, comprising a collection of eight CD-ROMs. In addition to the scientific measurements made by the Ulysses experiments, this CD-ROM archive also contains background articles about the Ulysses mission, extensive instrument documentation and plots of selected data parameters.

The Ulysses Solar Minimum Mission CD-ROM archive is the first release of Ulysses data on a permanent storage medium by ESA, and complements the ESA Ulysses data archive which can be accessed through the Internet. Updates to this CD-ROM archive and further releases of Ulysses data are planned for the future.



Introduction

The joint ESA/NASA Ulysses mission, launched on 6 October 1990, to explore the heliosphere at high latitudes for the first time, completed its prime mission (Fig. 1) in September 1995 and is now on a second solar orbit (Fig. 2). The spacecraft provided continuous scientific measurements during its in-ecliptic transfer to the Jovian system (see ESA Bulletin No. 67), its flyby of the giant planet (see ESA Bulletin No. 72), its descent to the south solar pole (see ESA Bulletin No. 82), and its ascent over the north solar pole (see ESA Bulletin No. 92).

Ulysses data are available to the scientific community on the Internet through the ESA Ulysses data archive (see ESA Bulletin No. 86) at:

http://helio.estec.esa.nl/ulysses/archive/

and general information about the Ulysses mission can readily be found at the ESA Ulysses mission Internet site at:

http://helio.estec.esa.nl/ulysses/

Independent archives of Ulysses data also exist in the United States and are managed by the National Space Science Data Center (NSSDC) and the Planetary Data System (PDS) on behalf of NASA. Archiving activities between ESA and NASA are coordinated where appropriate, and the data-set holdings are essentially identical.

The subset of Ulysses measurements taken during the first orbit, from launch to the end of the first north polar pass on 30 September 1995, have now been collected together and issued as an ESA Special Publication (ESA SP-1230) comprised of eight CD-ROMs. This constitutes the first release of Ulysses data by ESA on a permanent storage medium and complements the wider set of Ulysses data already available on the Internet through the ESA Ulysses data archive.

The Ulysses data sets

The scientific payload of Ulysses comprises (Fig. 3):

- two magnetometers (VHM/FGM) to provide high-resolution measurements of the interplanetary magnetic field
- a solar-wind plasma instrument (SWOOPS) to derive the bulk properties of the solar wind
- a solar-wind ion composition experiment (SWICS)
- three sets of charged-particle detectors (EPAC, HI-SCALE and COSPIN) to quantify ion and electron fluxes over a wide range of energies and for many ion species
- a combined radio- and plasma-wave instrument (URAP)
- a solar X-ray and γ-ray burst detector (GRB)
- a cosmic-dust experiment (DUST), and
- an interstellar neutral-gas instrument (GAS).

Radio-science experiments have also been performed (SCE and GWE) making use of the spacecraft's radio communication link in specific periods.

Each experiment team is led by a Principal Investigator (PI), and involves Co-Investigators (Co-I's) from European and American institutes (Table 1). In total, more than 120 scientists are directly associated with one or more of the investigations.

Each PI team has been responsible for generating the data sets available for the Ulysses data archives and for the new CD-ROM collection. The data sets represent the best combination of parameter selection and time resolution for typical scientific studies, taking into account data-reduction techniques, intervals affected by noise, contamination or missing records, and overall data-set size. Adequate documentation is provided to accompany the data sets, together with points of contact for data production within each PI team.

Ulysses data collected during the flyby of Jupiter have been previously archived by the Planetary Plasma Interactions (PPI) node of the Planetary Data System (PDS), and are available both on-line at the PPI/PDS Internet site, and also on CD-ROM. The Jupiter data sets are generally provided at higher time resolution than throughout the rest of the mission, and may also differ in parameters supplied.

The CD-ROM archive format and content

The Ulysses Solar Minimum Mission CD-ROMs are formatted to conform to the ISO 9660 standard with level-2 compliance, allowing file names longer than eight characters. They can be mounted on any hardware platform with a CD-ROM reader supporting this standard.

The CD-ROMs are designed and optimised to be viewed with an Internet browser such as Netscape or Internet Explorer, but can also be accessed as a conventional data disc. The Jupiter CD-ROM provided by PPI/PDS also conforms to PDS standards and includes PDS products for navigation (PDS Explorer on Windows platforms only) and for plotting (SPLASH).

The eight CD-ROMs of ESA SP-1230 have been arranged in such a way as to group Ulysses data sets from a particular type of measurement together, with the physical storage

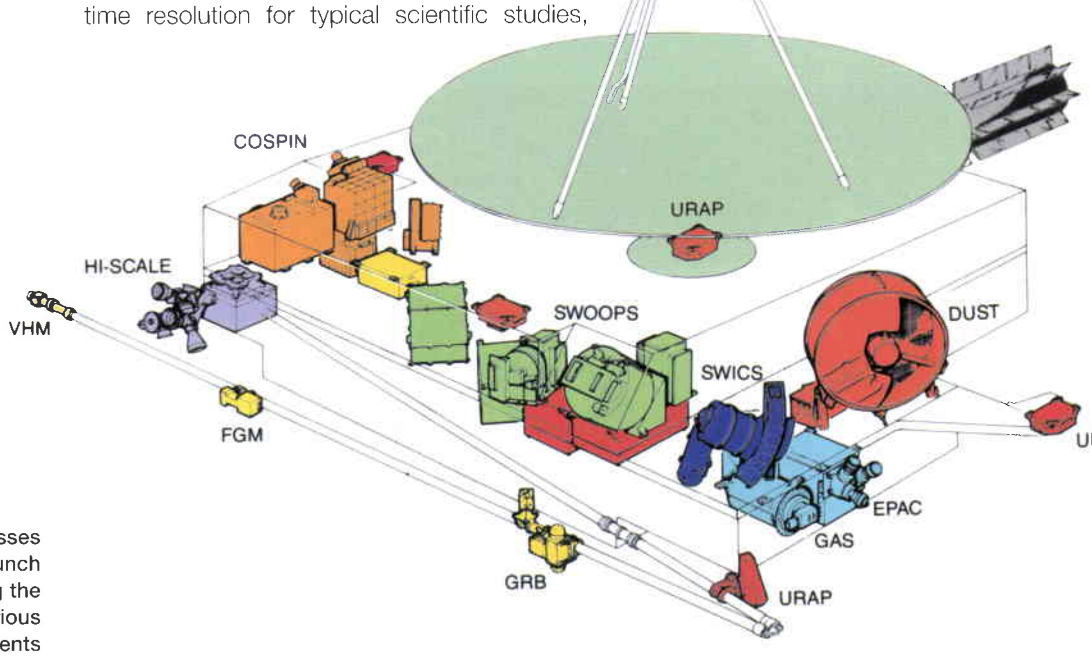


Figure 3. The Ulysses spacecraft in launch configuration, showing the locations of the various instruments

Investigation	Acronym	Principal Investigator	Measurement
Magnetic field	VHM/FGM	A. Balogh, Imperial College, London (UK)	spatial and temporal variations of the heliospheric magnetic field: 0.01 to 44000 nT
Solar-wind plasma	SWOOPS	D.J. McComas, Los Alamos National Lab. (USA)	solar-wind ions: 260 eV/q to 35 keV/q; solar-wind electrons: 0.8 to 860 eV
Solar-wind ion composition	SWICS	J. Geiss, ISSI, Bern (CH) G. Gloeckler, Univ. of Maryland (USA)	elemental & ionic-charge composition, temp. and mean speed of solar-wind ions: 145 km/s (H^{+}) to 1350 km/s (Fe^{+8})
Radio and plasma waves	URAP	R.J. MacDowall, NASA/GSFC (USA)	plasma waves, solar radio bursts, electron density, electric field plasma waves: 0-60 kHz; radio: 1-940 kHz; magnetic: 10-500 Hz
Energetic particles and interstellar neutral gas	EPAC/GAS	E. Keppler, MPAe, Lindau (D)	energetic ion composition: 80 keV-15 MeV/n neutral helium atoms
Low-energy ions and electrons	HI-SCALE	L.J. Lanzerotti, Bell Laboratories, Lucert Technologies, New Jersey (USA)	energetic ions: 50 keV-6 MeV energetic electrons: 40-400 keV
Cosmic rays and solar particles	COSPIN	R.B. McKibben, Univ. of Chicago (USA)	cosmic rays and energetic particles ions: 0.3-600 meV/n electrons: 4-2000 MeV
Solar X-rays and cosmic gamma-ray bursts	GRB	K. Hurley, UC Berkeley (USA)	solar-flare X-rays and cosmic gamma-ray bursts: 15-150 keV
Cosmic dust	DUST	E. Grün, MPK, Heidelberg (D)	dust particles: 10^{-16} to 10^{-7} g
Coronal sounding	SCE	M.K. Bird, Univ. of Bonn (D)	density, velocity and turbulence spectra in the solar corona and solar wind
Gravitational waves	GWE	B. Bertotti, Univ. of Pavia (I)	Doppler shifts in S/C radio signal due to gravitational waves

limitation of approximately 600 Mbytes per disc being the overriding constraint for the content of each disc. An example of the CD-ROM label design is shown in Figure 4.

The data content of each of the eight discs is as follows:

Disk 1: Magnetic-field data (VHM/FGM), solar-wind data (SWOOPS and SWICS), charged-particle data (EPAC) and interstellar neutral-gas sky maps (GAS)
Disk 2: Charged-particle data (HI-SCALE and COSPIN), dust impact measurements (DUST) and radio sounding data (SCE)
Disks 3-4: Radio- and plasma-wave data (URAP)
Disks 5-7: Solar X-ray and cosmic GAMMA-ray data (GRB)
Disk 8: Data from the Jupiter encounter (supplied by PPI/PDS).

In addition to the data sets listed above, each disc (with the exception of disc 8) contains plots of selected data parameters for predefined 26-day periods (corresponding approximately to the synodic solar rotation period), yearly intervals and over the complete time period covered by the Solar Minimum Mission. Comparison between plots of different data parameters from experiments grouped on the same disc is simplified when an Internet browser is used to survey the plots. Sky maps and summary plots provided by certain PI teams can also be best viewed using a browser interface. Figure 5 is an example of a plot, showing magnetometer data from launch to the end of the first north polar pass. Figure 6 shows an example of a daily summary plot of radio- and plasma-wave intensities provided by the URAP team and Figure 7 depicts a typical sky map from the GAS experiment.

Figure 4. Label of the first of the eight CD-ROMs of ESA SP-1230

The IDL software modules developed to generate the 26-day plots are also provided on the discs, with accompanying documentation to allow a user familiar with IDL to produce plots for different time intervals.

Each disc also contains general information about the Ulysses mission, including details about the spacecraft, its trajectory (in various coordinate systems), the instruments, a description of some of the major scientific results, a collection of images (photographs and artwork), and a recent list of publications written using Ulysses data.

CD-ROM updates and future releases

The issue of this ESA Special Publication constitutes the first of several releases of Ulysses data, data products and mission information on CD-ROM and other permanent media. A description of any errata that are found to exist on the Solar Minimum Mission archive will be posted on the ESA Ulysses data archive Internet site. This is also the location of the most recent Ulysses data released to the public.

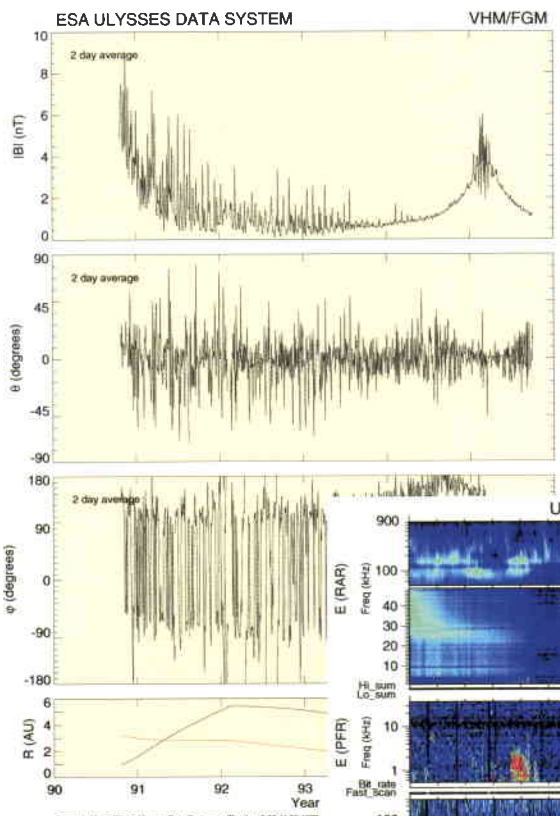


Figure 5. Magnetic-field measurements made by the VHM/FGM experiment on Ulysses during the Solar Minimum Mission. The magnetic field magnitude and components (θ and φ) are shown, together with the radial distance from the Sun and the heliographic latitude of the Ulysses spacecraft

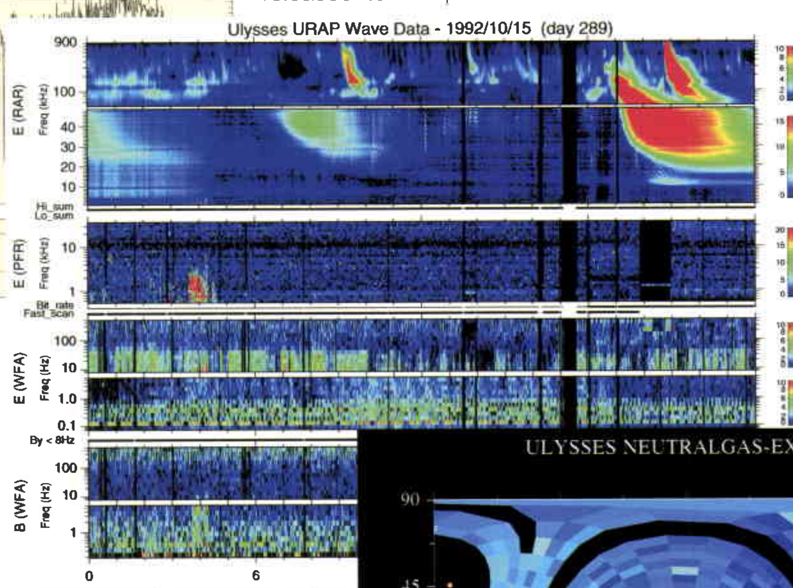


Figure 6. A typical daily summary plot of URAP radio and plasma wave data (courtesy of R. MacDowall)

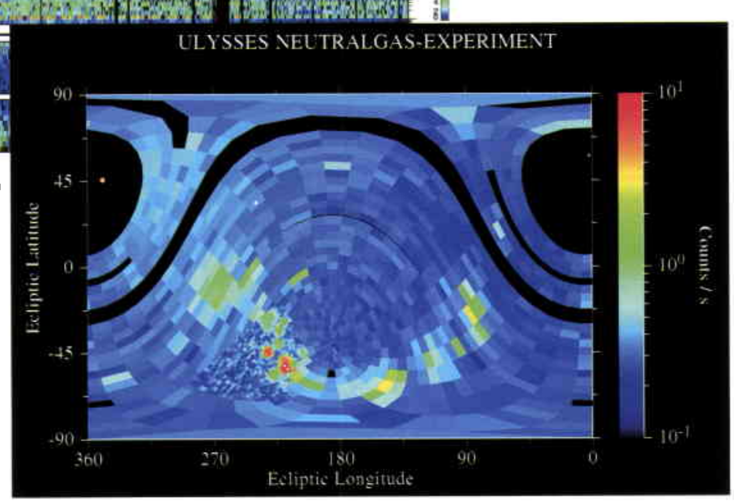


Figure 7. A typical sky map from the GAS experiment (courtesy of M. Witte)

If important (re-)submissions of Ulysses data for the first solar orbit become available, formal updates to individual CD-ROMs in the collection will be considered.

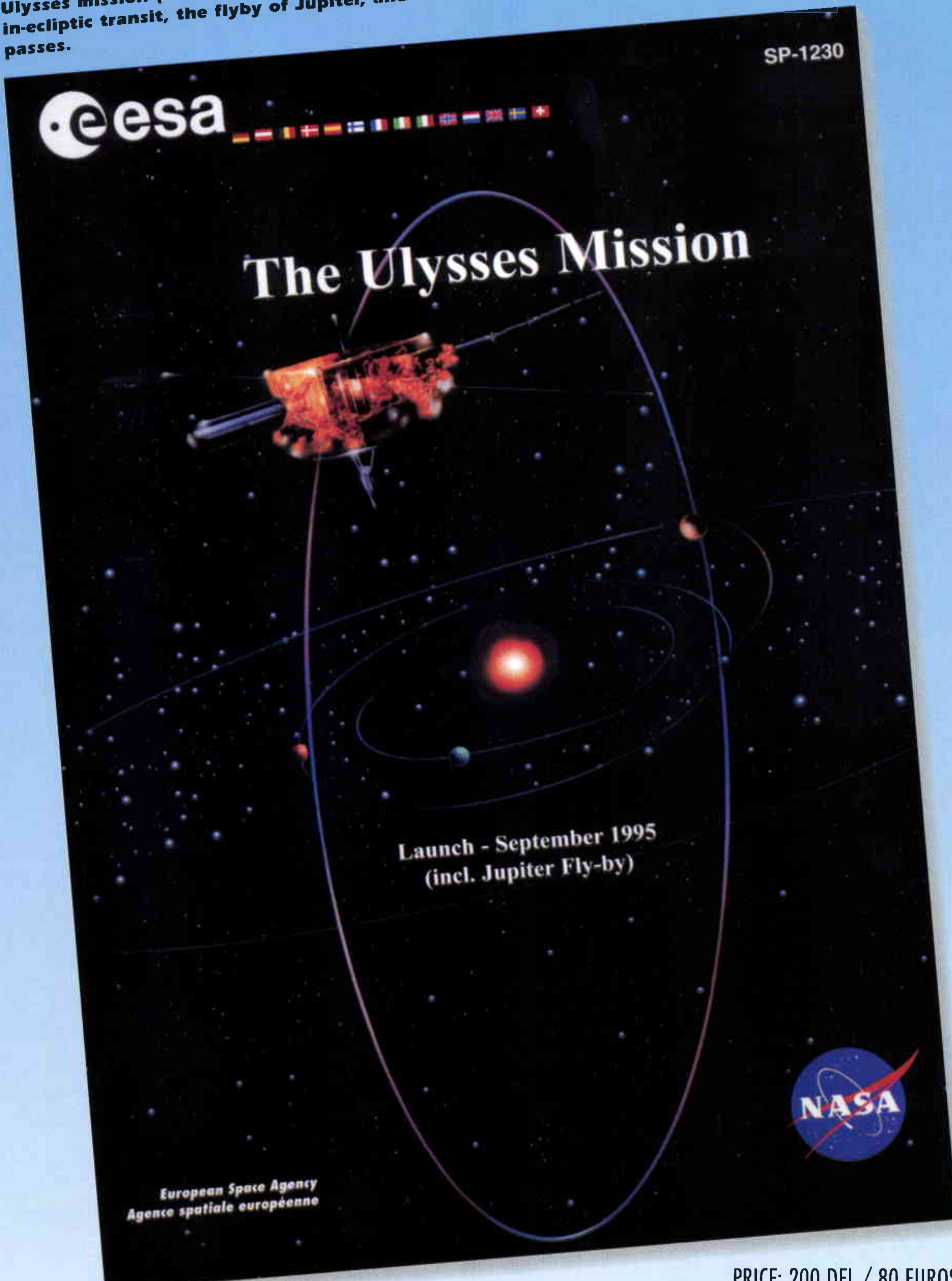
Data from the second solar orbit, currently available online over the Internet, will also be distributed on a permanent storage medium in the near future. Given the foreseen increase in the number of CD-ROMs required to accommodate the extra data already accumulated during the second orbit, an alternative to CD-ROMs will be considered. One possibility is to collect the data on a small number of DVD-ROMs. The choice of this medium for data storage is currently premature, given the limited availability of hardware and software to write data DVDs. However, the situation is expected to improve over the next couple of years, offering up to 20 Gbytes of storage per DVD disc, as opposed to the (maximum) 650 Mbytes available with CD-ROMs.

In summary, the release of Ulysses data for the Solar Minimum Mission as a collection of eight CD-ROMs will complement the existing online archive of Ulysses data. It will also provide a source of data to compare with the new measurements that the spacecraft will make as it crosses the solar-polar regions for a second time, during the active phase of the eleven-year solar cycle.

ESA SP-1230 can be obtained directly from the ESA Publications Division at a cost of 200 DFl or 80 Euros.

esa

This ESA Special Publication consists of a set of 8 CD-ROMs carrying data submitted to the ESA and NASA archives by the Ulysses Investigator Teams for the first phase of the Ulysses mission (launch up to the end of the second polar pass). This period covers the in-ecliptic transit, the flyby of Jupiter, and the first (south) and second (north) polar passes.



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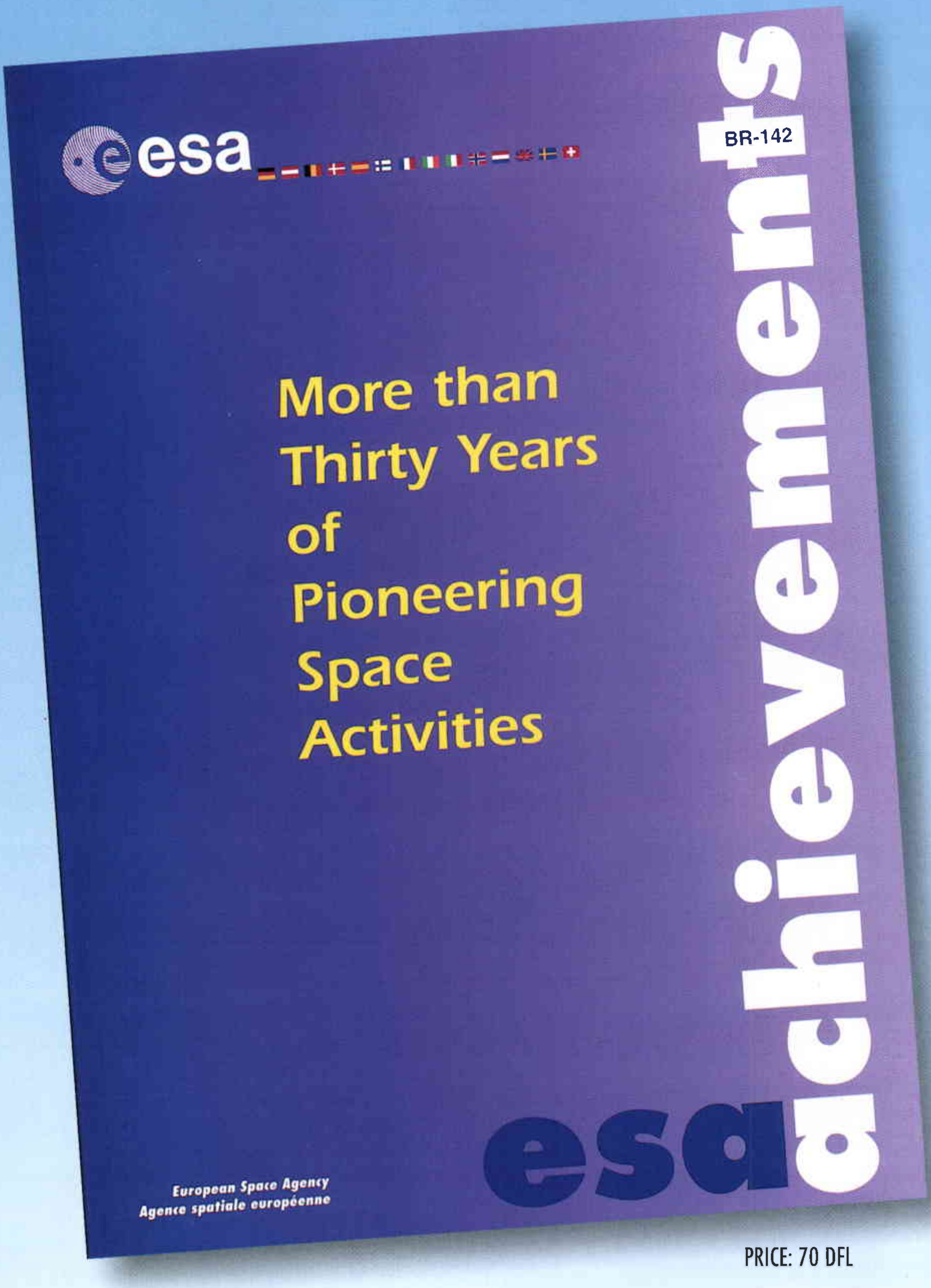

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ESA's Home Page on the World Wide Web – A Recap

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Initiated in November 1993, the ESA Home Page has come a long way from the time when it provided just some basic information on the Agency and access to some of its information systems. Today, it forms part of the Agency's corporate identity, providing up-to-date information on all of its programmes. It also offers links to other areas and aspects of the fascinating world of space and its associated technology, making this portal a reliable source of up-to-date space information for the general public.

Early days

The ESA Home Page began as a pilot project with just some basic information, which included an overview of the Agency's activities, a link to its Establishments, which at the time provided some local information on their individual activities, as well as links to other services offered within ESA which were already accessible via the World Wide Web.

Figure 1. An early version of the ESA Home Page

The ESA Home Page itself was put on line in November 1993 with the aim of informing the general public about the Agency, and providing links to some of the initiatives being taken within ESA in experimenting with the Web technology (e.g. the Earth Observation Guide and Directory Service (EO-GDS) and the European Space Information System (ESIS)). Several layouts were tested at that time, including a map of Europe depicting ESA's centres. The initial site of the ESA Home Page, mainly run from ESRIN, used the hypertext transfer protocol (http), while the ESTEC site was running from a File Transfer Protocol (ftp) server.

Later on, as the Web began to emerge as a major information carrier and styles evolved to incorporate links to other services and other information (Fig. 1). The home pages had to become more dynamic; they had not only to cater to a variety of services being created around each organisation, but they also had to provide the latest information at a glance.

The subsequent steps

It was soon evident that the brochure-like information being displayed on the ESA Home Page was not enough. There had to be more, much more. The Press Releases and Information Notes, which provided a wealth of information on current issues, were migrated from a simple terminal layout to a more attractive Web layout. What you printed was what you saw on the screen. A simple subscription form was created, whereby users merely pointed their Web browsers to subscribe to and regularly receive all Press Releases and Information Notes that were being published via e-mail.

In parallel with these activities, other areas within the Agency also began making special services available via the Web. One worthy of mention is the ESA Publications Division, whose Web site went online in the summer of 1994. The ESA Annual Report, Bulletin, Newsletters and other publications were made available electronically to their worldwide readerships for the first time.

The ESA Web Help Desk became operational in November 1995. Its task was to provide assistance to the outside world in gaining access to the various services being offered, and to answer all of the customer queries, of both a technical and a non-technical nature, that such an on-line service generates.

One of the most innovative of the early activities, in which ESA Public Relations was involved, was the 'Your Signature into Space' initiative. The idea was to develop a Web interface to allow young and old alike to write a message, or draw a picture, that would ultimately find its way into space on board ESA's Huygens scientific mission, launched on 15 October 1997. A special CD was created and placed on the spacecraft, which is now on its way to Titan, one of planet Saturn's moons.

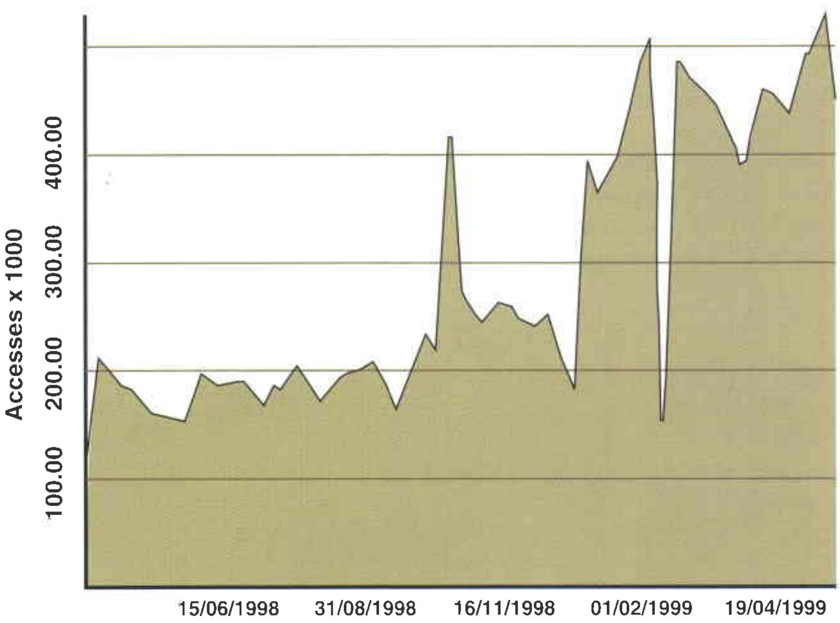

Figure 2. ESA Home Page access statistics from June 1998 to May 1999, showing a doubling in the number of accesses over the 12-month period

The live effect

One of the most profound effects of the new medium, which was taking off on a global scale, was the ease and speed with which information could be disseminated. During the first Ariane-5 launch, for example, the public's thirst for up-to-the-minute information almost brought the ESA Home Page server to a standstill. Accesses shot up during the busiest period to more than 100 per minute. During the week of the Ariane-502 launch, which took place on 30 October 1997, there were almost 600 000 accesses, with a peak of 44 000 accesses/hour during the launch itself.

The type of information made available during the Ariane-5 launch ranged from background information on the launcher itself, to Press Releases giving details about progress in the days leading up to the launch, as well as links to live broadcasts by television stations across Europe.

Interest in the Internet elsewhere within the Agency began to grow as a clearer picture of the capabilities for disseminating information quickly and efficiently via the Web began to emerge. Several Programme Directorates - Science, Earth Observation, and Manned Space Flight and Microgravity - all of whom hold vast sources of information, became more Web-oriented in their approach and reporting.

Special events

The Ariane-501 launch was the first event for which ESA and CNES closely coordinated their respective Web activities. The idea was to provide an interconnected bilingual site allowing the 'visitors' to choose between French and English.

In another initiative, ESA, along with several other international organisations in Europe (notably the European Southern Observatory and the European Union), got schoolchildren involved with a Web site that covered a wide range of space-related activities. This project, known as 'Sea and Space' (see ESA Bulletin No. 97, pp. 28-31), allowed school children to propose projects involving images from ESA's remote-sensing satellites, as well as astronomical projects, and navigation projects using a GPS instrument. 'Sea and Space' was a huge success, proving that European schools were indeed ready to use World Wide Web technology and that many already had the infrastructure to do so.

Another example of close collaboration involved the setting up of a joint site with Eumetsat for the Meteosat Second Generation (MSG) programme. In this particular case, it was decided to share the content as well as to agree on a common layout. Each organisation maintains its own MSG portal with its own style. Responsibility for content and updating is shared, with specific pages being maintained by each organisation. The resulting Web site has been a good demonstration of how the latest technology can play an essential role in sharing information content and keeping it up-to-date.

Established services

What sort of information can be found via the ESA Home Page? The ESA Convention can be accessed in its entirety, for example. High-

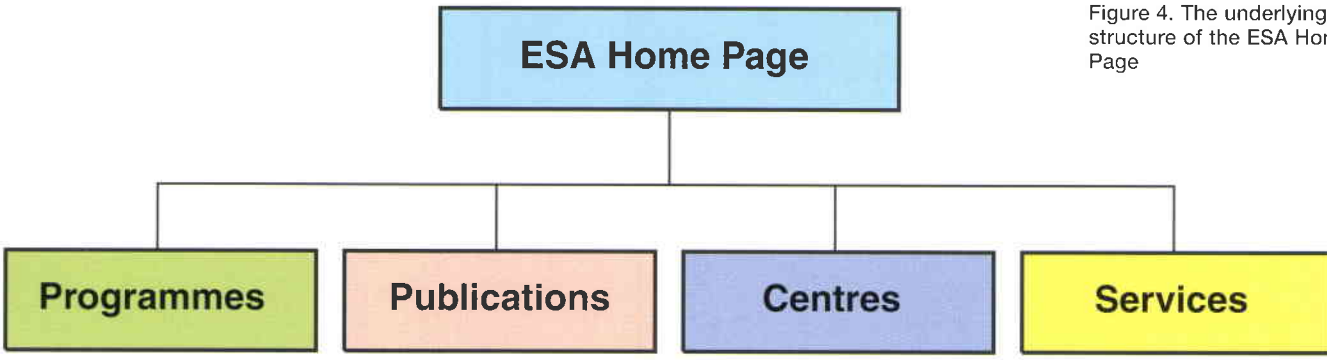

Figure 4. The underlying structure of the ESA Home Page

resolution images for all of the Agency's missions and the photographs and biographies of the ESA astronauts may also be found there. The video archive provides the possibility to search through ESA's video library and to order specific videos. A special slide presentation all about ESA's activities, its structure and its future missions can also be viewed via the Web. One can also dig deeper to find out, for example, about the very interesting conferences, symposia and workshops that take place regularly at the various ESA establishments. The ESA Home Page also provides a calendar of the current and future public-relations-oriented events that are taking place.

Within the short span of just one year, the number of accesses to the ESA Home Page has increased dramatically, due not only to the amount of information that is being made available, but also the increased frequency in its updating (Fig. 2).

Structure

Today, the ESA Home Page is actually composed of several sites, all loosely linked to the top (entry) page (Fig. 3). This not only allows maximum flexibility and freedom for the various areas of the Agency to maintain and update the pages on their particular activities, but has also stimulated a certain degree of creativity. The main components of the current site are shown in Figure 4.

Figure 3. The current ESA Home Page

The future

In the past several years, the global flow of information has increased dramatically. The Internet has become *the* communications tool of the modern age. As network connectivity improves, more of the conventional methods of communication will make use of this technology.

It is already taken for granted that one can watch the news whenever one wants. One can access authoritative information at the source. Once can do serious research using the resources available on the Internet. One can even control equipment remotely to carry out a specific task!

As for communication, the virtual studio, in which several remote participants 'can sit next to each other', is not very far away. A walk through the Space Station during a 'virtual open day' could also soon become a reality!

The Microgravity Measurement Assembly

Post-Mission Data Analysis for Spacelab MSL-1

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The Microgravity Measurement Assembly can provide researchers and flight crews aboard manned spacecraft with real-time displays of microgravity-level accelerations, down to the Quasi-Steady Component. This article describes the system's performance on the MSL-1 Spacelab mission, and its potential for the International Space Station.

The MMA system

The Microgravity Measurement Assembly (MMA) is a microgravity-monitoring system capable of providing investigators and onboard crews with a real-time display of the accelerations detected by up to seven sensor heads, five of which can be deployed in racks where microgravity-sensitive investigations are carried out. MMA provides on-line analysis of the acceleration data by means of typical signal processing techniques.

MMA, developed by ERNO (now DASA-RI, D), made its first, successful, flight on the German Spacelab-D2 mission in April-May 1993. The D2 mission triaxial sensor heads, called Microgravity Sensor Packages (MSPs), are based on capacitive micromechanical silicon-chip technology. They are sensitive to disturbances of 10^{-5}–$10^{-2}g$ within the frequency range 0.1–100 Hz. The analogue acceleration data, sampled at 300 Hz, as well as temperature data from the sensor heads, are digitised by dedicated Microgravity Sensor Electronics (MSE) boxes and then routed to the central Modus 8086 computer. It adds time tags to the data sets to provide exact time correlation of the data and multiplexes the sets into one data stream, which is continuously downlinked to the ground via the Spacelab High Rate Multiplexer (HRM) and the Experiment Computer Input/Output (ECIO) throughout the mission. On the ground, the flight segment is complemented by the MMA Ground Station (GST) of two parts: the Front-End PC (FE-PC) for continuous acquisition of the HRM data and their archiving on optical disks, and the Display Unit (DU), which receives data from the FE-PC and generates analogue recordings from each microgravity sensor (axis by axis) and displays any one of them in either time or frequency domain as defined by the operator.

MMA on the LMS, MSL-1 and MSL-1R Spacelab missions

Owing to the appreciation by microgravity scientists of the MMA data and services made available to them during the D2 mission and to the support from NASA's Glenn Research Center (formerly the Lewis Research Center), the MMA was offered new flight opportunities: the Life & Microgravity Spacelab (LMS) Mission on STS-78 in June-July 1996; the Microgravity Science Laboratory (MSL-1) Spacelab Mission on the shortened STS-83 in April 1997, and the MSL-1R mission on STS-94 in June-July 1997.

For the reflight missions, MMA was significantly enhanced by the integration of the tri-axial nano-accelerometer ASTRE (Accéléromètre Spatial TRiaxial Electrostatique), developed by ONERA (F). ASTRE is based on the servo-controlled electrostatic suspension of one single proof mass and is sensitive to disturbances of 10^{-9}-$10^{-3}g$ within the frequency

Figure 1. MSL-1 astronaut Bob Thomas activating MMA during training

range 10^{-4}–2.5 Hz at a resolution of $10^{-9}g$. ASTRE was specifically developed in order to extend MMA's sensitivity into the quasi-static and low-frequency range. It is able to measure the lowest components of the onboard residual acceleration down to one orbital period: atmospheric drag, gravity gradient and out-of-plane component.

MMA's ground segment was also improved. Real-time signal analysis software packages are used in the up-to-date Graphics Display Unit, developed by LMS-I (B). Using the playback function, the DU can perform detailed data analyses offering a wealth of tools including zooming, windowing, 3D displays, real-time display of multi-channel time histories, Fourier analysis, power-spectrum density and coherence functions. At the same time, the DU can be configured to produce plots of both time and frequency domain data automatically as well as taking JPEG screen shots that are automatically transferred to the web pages accessible to scientists all over the world. The real-time analyses of acceleration data synchronised with the onboard clock help the scientists to promptly assess the measured versus required microgravity environment, and to plan for possible corrective actions on their own experiments, such as the repetition of experiment runs where the microgravity levels were exceeded and the interruption of experiment runs during crew exercise periods. Besides classical signal-processing capabilities, the software packages are tailored to the specific MMA requirement to extract on-line the quasi-steady component out of the MMA data. The execution of such functionality, which intrinsically requires the processing of huge amounts of data, digital filtering and resampling capabilities, was proved to be difficult within the specific Spacelab mission operative constraints, where a significant degree of data interruptions/corruption was systematically experienced. An encouraging signal in phase with the sunset/sunrise transition was extracted within the MSL-1R timeframe, out of a 1.5-orbit-long data string. Systematic post-mission data analysis was initiated with ONERA and LMS-I to confirm the result, to prove its repeatability for different orbits and its consistency with predictions based on orbital and atmospheric parameters.

The mission statistics

MMA MSL-1R data collection

The whole 27 GB MMA data files from MSL-1R are held on 46 CD-ROMs, holding mostly four 150 MB files of 2 h of flight binary data on each disk. Each file corresponds to binary data including the characteristics of the data formatting and the acceleration measurements (3-axes outputs) of each MSP or of ASTRE and the temperature survey. Most of the extracted accelerations and temperature data are constituted in ASCII files by ONERA, one per axis and per 2 h period, and the data concerning ASTRE are plotted in reference data books.

As the bandwidth of ASTRE is rather low (2.5 Hz), a first mean computation over 3.3 ms is performed on the acceleration measurements, transforming the initial data sampling (300 Hz) into 100 Hz. This matches the filtering of all the MMA sensor heads with a 6th order Butterworth lowpass (100 Hz cut-off).

Statistical analysis of the whole mission

The acceleration measurements provided by each MMA sensor are expressed in each instrument own-axes reference. With the aim of comparing the accelerations measured by the sensors, the Orbiter Body coordinate system defined for all Orbiter activities is chosen as the unique reference system. The origin of its axes is the Orbiter's centre of gravity. Positive X_B is towards the Orbiter nose, positive Y_B is out of the right wing and positive Z_B is towards the bottom of the Orbiter fuselage.

A statistical analysis was performed on the whole acceleration data measured by ASTRE at 100 Hz to determine the measurement distribution inside different orders of magnitude: the averaged percentages obtained along the three instrument axes are respectively equal to 1.7% for measurements out of range (>1 mg), 0.7% between 1 mg and 100 µg, 37.6% for 100–10 µg and 60% less than 10 µg. About 97.6% of measurements are <100 µg. The best results are obtained along the instrument-sensitive Z_{AST} axis corresponding to the X_B

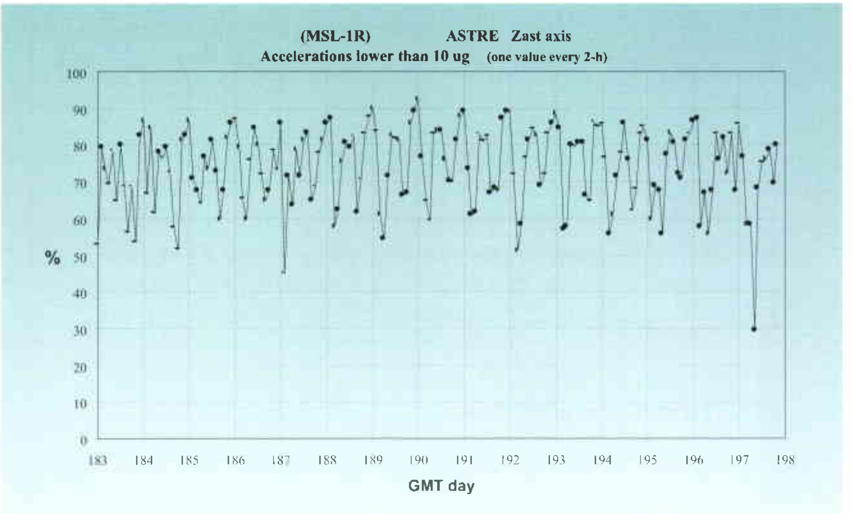


Figure 2. Percentages of the ASTRE data lower than 10 mg along the instrument Z_{AST} axis (X_B) during the whole of mission MSL-1R

axis. About 74% of the measured accelerations along this axis are <10 μ*g*, against about 55% along the two other axes.

For MSL-1, the crew divided into two teams (Red and Blue) with their activities and sleep phases shifted. One or other team was always active over the whole mission. The crew schedule is visible in Figure 2, which shows the statistical data analyses performed on the ASTRE acceleration measurements of 10 μ*g* over periods of 2 h. The best results are obtained during the sleep phases of the Red team between 22 h and 2 h. Data from the Blue rest periods, between 10 h and 14 h, are of less interest for this analysis.

Identification of quiet periods

The quasi-steady accelerometric environment is mostly due to the aerodynamic Orbiter drag and to the tidal effects, combined effects from the gravity gradient acceleration and the centrifugal acceleration. The overall quasi-steady contribution depends mostly on the Orbiter orientation defined by the Orbiter attitudes expressed by the pitch, yaw and roll angles of the Orbiter Body reference frame with respect to the Local Vertical Local Horizontal attitude frame. For this latter reference, positive x_{lv} is towards the velocity vector, positive y_{lv} corresponds to the cross-track direction, while z_{lv} is towards the centre of the Earth. This frame rotates as the Orbiter moves around the Earth. Two main Orbiter attitudes were used during STS-94: (-ZN/55 Roll) and (-ZN/45 Roll) with the negative X_B being along the velocity vector. Their pitch angle is 180°, their yaw angle is null and their roll angle equals 55° and 45°, respectively. In these (-ZN/Roll) orientations, the maximum of the tidal effects is observed on the Y_B and Z_7 axes, while the atmospheric drag is mostly along X_B.

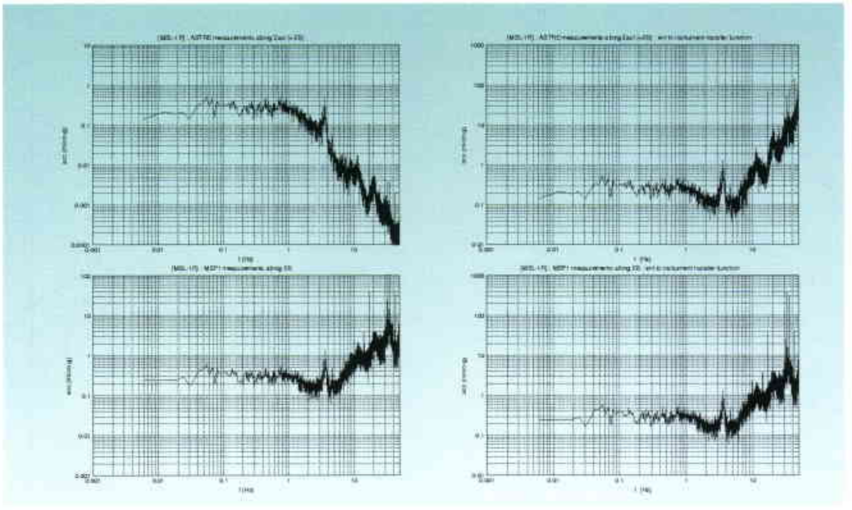
The analysis of the ASTRE measurements concerning the extraction of the residual quasi-DC components was performed for the quietest periods when the crew had the least activities, leading to less disturbed accelerations, and when the Orbiter orientation matched the selected ones. Six quiet periods of 6 h (about 4 orbits) were selected: five during Red sleep phases from about 20:00 GMT (respectively during days 189, 191, 192, 193, 195) and one during the Blue rest time from GMT 190/09:00.

Comparison between ASTRE and MSP1 measurements

Comparison of the outputs of ASTRE and MSP1 was performed in the frequency domain during the period on GMT 193/12 selected as a representative example when four Red astronauts were active. The amplitude spectra are illustrated in Figure 3 along the X_B axis. The spikes detected by ASTRE and MSP1 1–10 Hz correspond mostly to the structural modes; the mode at 3.6 Hz is particularly visible. The drop, seen on all the ASTRE spectra, is in agreement with the instrument frequency bandwidth. These plots show the complementary domains of the frequency bandwidth of ASTRE and MSP1, the common frequency band being observed approximately at 0.1–2 Hz. The spikes of the Ku-band antenna at 17 Hz and its first harmonic are well identified by MSP1 and ASTRE, although this frequency is much beyond the upper limit of ASTRE bandwidth.

Then, the ASTRE and MSP1 measurements were corrected using the instrument transfer functions in the bandwidth from DC to 50 Hz. The resulting spectral levels along the X_B axis are presented in Figure 3. Very fine correlation of the spectra is seen up to 50 Hz. Some differences of scale factor are observed for frequencies >20 Hz for the three axes. This demonstrates that ASTRE can detect the vibration levels up to 50 Hz frequency, the resolution of the instrument being better than 1 n*g* at lower frequencies and less, but sufficient, at higher frequencies.

Figure 3. Sensor outputs in the frequency domains along X_B. Upper plots for ASTRE, lower plots for MSP1; the right-hand figures are after correction from the instrument transfer functions



Comparison between ASTRE and OARE measurements

The quasi-steady measurements provided by ASTRE can be compared with those produced by the Orbital Acceleration Research Experiment (OARE) from NASA Glenn. Like ASTRE, this accelerometer is designed for measurements in the low frequency band and for amplitudes <1 µ*g*. OARE is located outside the Spacelab module in the Orbiter payload bay, close to the centre of gravity.

The ASTRE and OARE outputs were compared from GMT 195/18 (one of the selected quiet periods) over 10 h, as presented in Figure 4. The OARE data are sampled at 25 s after a trim-mean filtering over 50 s periods. In order to achieve a better comparison, ASTRE data are processed in a similar way by averaging the initial data over 50 s periods overlapped by half of their length to get a sampling time of 25 s. All the initial ASTRE data outside the range ±30 µ*g* are eliminated within the average time period.

Along the X_B axis, corresponding to the main drag component direction, very fine correlation of data are observed in the left plots of Figure 4 over the first 6 h. A calibration phase observed in the OARE plot leads to a DC level shift that is not observed by ASTRE.

Along the Y_B axis, seen on the middle plots of Figure 4, the acceleration variations are larger for ASTRE because of its location inside the Orbiter. The accelerations from the rotational effects are mostly responsible for the data differences.

Along the Z_B axis, shown in the right plots of Figure 4, the acceleration variations are larger for ASTRE, again arising from the accelerometer's location but also because of the fluctuations observed along this carrier axis. These results show that the stability of the ASTRE DC levels along the two instrument sensitive axes (X_B and Y_B) is at least as good as the residual bias of the OARE data between two calibration phases. As an example, Orbiter manoeuvres are clearly detected by ASTRE.

MSL-1R quasi-steady environment

Orbital periods

According to NASA's mission timeline, the period of the Shuttle orbit crossing the equatorial plane varied from 5418 s to 5421 s. This verifies the measured value of about 5400 s.

Accelerations due to the surface forces acting on the Orbiter

The surface forces acting on the Orbiter are mostly atmospheric drag plus the radiation pressures from the Sun and Earth. At the Orbiter altitude of about 300 km, the acceleration from radiation pressure was negligible compared with the drag components.

The atmospheric drag was evaluated at ONERA using NASA's MSL-1R parameters and from the Drag Temperature Model (DTM) of Barlier. This model takes into account the temperature of the atmosphere and the atmospheric density with respect to the Orbiter altitude and to the solar-diurnal and geomagnetic effects. The relative velocity of the Orbiter was deduced from the predicted trajectory.

The simulation provides the atmospheric density, the drag module and components every 300 s over a large period of nearly 46 h between two manoeuvres from about GMT 195/08. Figure 5 shows the evolution of the drag in the Orbiter Body reference frame for the selected zone with a zoom over the 6 h (4 orbits) of the quiet zone. During this latter zone,

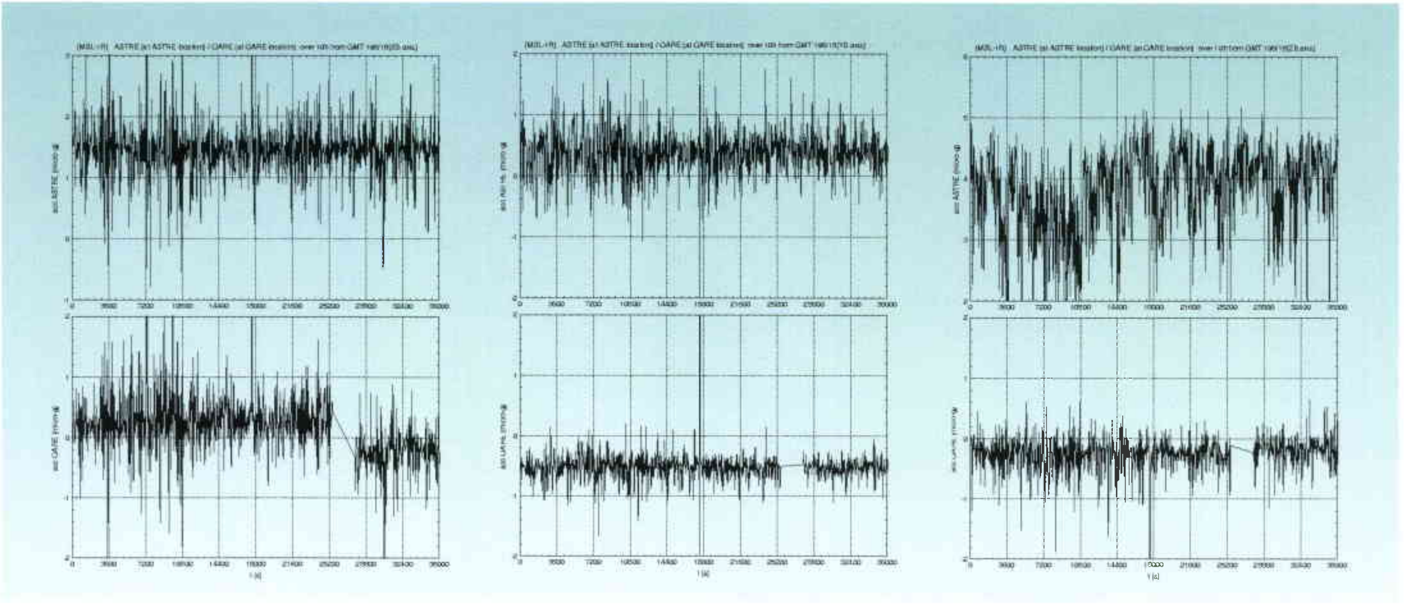


Figure 4. ASTRE (upper plots) and OARE (lower plots) accelerations measured from GMT 195/18 over 10 h along each B axis

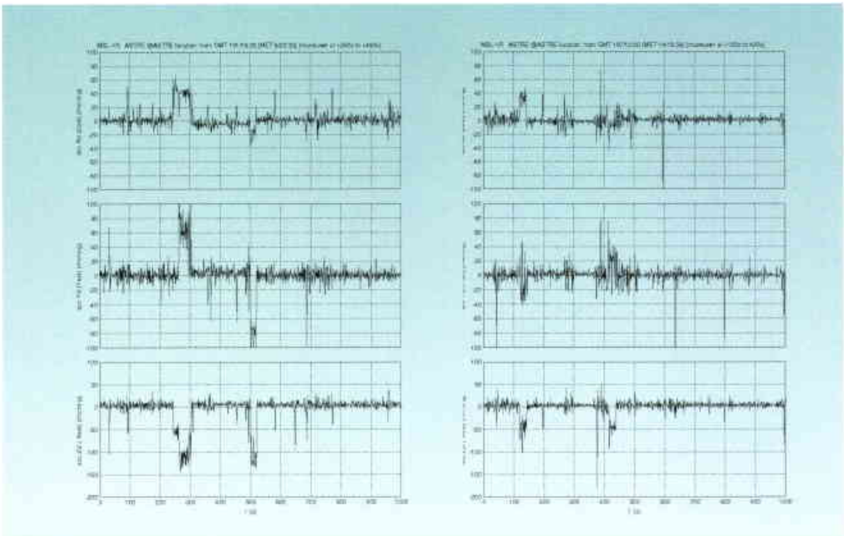


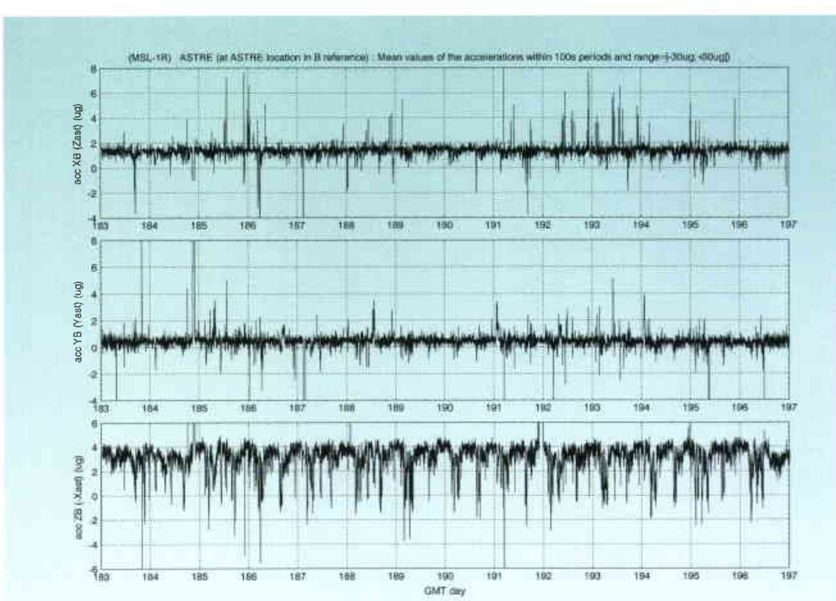
Figure 5. Evaluation of the drag modelled by the Drag Temperature Model of Barlier along each B axis from GMT 195/00. Amplitudes in mg versus time in hours

the amplitude mean value is evaluated respectively to be 0.185 μg, -0.002 μg and $-2x10^{-5}$ μg along X_B, Y_B and Z_B axes, while the maximal variations are respectively ±0.08 μg, ±0.006 μg and $\pm2x10^{-4}$ μg along the three axes.

Accelerations due to tidal effects
The accelerations due to the tidal effects were analytically evaluated according to the attitude angles of the Orbiter and to the accelerometer locations with respect to the Orbiter centre of gravity, close to its centre of mass. These accelerations are theoretically null along X_B owing to the compensation of the gravity gradient effects by the rotational effects during the main Orbiter attitudes.

Sensitivity of the quasi-DC results to the ASTRE temperature fluctuations
This analysis was undertaken in order to determine if the ASTRE temperature fluctuations influence the quasi-steady component extracted from the accelerometer measurements during the selected quiet periods.

Figure 6. Quasi-DC components of ASTRE data during the whole of MSL-IR along each B axis



The ASTRE proof-mass temperature, from which depends the instrument scale factor, was evaluated from the temperature measurements. Excluding time periods after launch and before landing, the averaged proof-mass temperature is about 26.3°C, with a total variation of 1.4°C. According to the nominal scale factor values and their thermal sensitivities along each instrument axis, this maximal variation leads to 0.3% variation on the scale factor of the ASTRE carrier axis (along X_B) and to 0.7% on the sensitive axes (along the two other axes). These corrections were carried out in the ASTRE data processing for the analysis of the quasi-steady components during the selected quiet periods.

Contributions to the ASTRE quasi-steady component
The contributions to the Quasi-Steady Component extracted from the acceleration measurements provided by ASTRE at the low frequencies were carefully examined for the selected quiet periods.

In order to limit the effects of large amplitude and high-frequency disturbances, the data (initially sampled at 100 Hz) outside the range ±30 μg were eliminated. This range covers at least 95% of the data in the quiet periods, corresponding to a gaussian distribution of $\pm2\sigma$ around the averaged amplitude.

The mean values of the remaining measurements inside the range R were computed over a 100 s sampling period (Fig. 6). The long-term stability of the DC level should be mentioned: during the whole mission, no drift is noticeable at the level of 0.1 μg or better on any the axis.

The quasi-DC outputs were also evaluated over subsequent 5400 s periods (about the orbital period). The sensitivity of the measurements to the Orbiter attitude and to the accelerometer locations with respect to the Orbiter centre of gravity are clearly demonstrated. The change of the Orbiter attitude, from (-ZN/45 Roll) to (-ZN/55 Roll) is particularly observable along Y_B on the averaged accelerations from days 194 to 197 compared to those obtained from days 189 to 193. The measurement difference (about 0.12 μg) corresponds to the difference evaluated for the ASTRE tidal accelerations with the Orbiter roll angle changing from 45° to 55°, i.e. 0.14 μg.

The same conclusions can be drawn for the accelerations measured by ASTRE and OARE due to their different locations within the Orbiter.

ASTRE biases of the order of 1 m*g* were evaluated along the sensitive axes, in agreement with the theoretical values and the resolution of better than 1 n*g*/(Hz)$^{1/2}$. Furthermore, the coherence of the results between the three missions (LMS, MSL-1 and MSL-1R) demonstrates the weak sensitivity of ASTRE characterisation to launch vibrations.

Proposals for the future

Lessons learned from the LMS and MSL-1 Spacelab missions

During the Spacelab missions, the MMA provided real-time feedback to users at the Payload Operations Control Centre (POCC) and off-line feedback to users in remote locations (such as User Centres in Europe) and the flight crew. The post-mission analysis of the MMA data extracted the QSC out of the recorded residual acceleration signal.

Some shortcomings became evident during the missions, as well as desirable improvements. In particular, the feedback to the remote users by means of a simplified GST and to the crew via a laptop would have been much more effective if made available in real-time. The capability for resetting the accelerometer sensitivity digitally proved to be desirable for adapting to the level of the onboard residual vibrations, which continuously changes and often saturates the accelerometers. Furthermore, scientists with experiments sensitive to the QSC (e.g. material science, fluid science) would have very much welcomed this information on-line.

Implementation/accommodation ideas for MMA on ISS

A next-generation MMA could be accommodated on the International Space Station (ISS). This system, based on a central processing unit (e.g. the standard payload computer, SPLC), should be capable of monitoring the microgravity environment in the frequency range DC to 400 Hz. The ISS-MMA should be modular, easily reconfigurable and expandable to adapt to the frequent changes of experiment facilities expected over the Station's long operational life. Autonomous and, possibly, remote operations are desirable in order to save crew time – the most valuable ISS resource. The existing MMA functionalities make possible the continuous mapping of the onboard microgravity environment over the Station's whole life.

The large amount of data, contrasting with the limited downlink rates, requires a unique effort to reduce the downlink data stream. This may be achieved via pre-processing of the onboard data, remote activation of dedicated sensors on request by a Principal Investigator (PI) or by

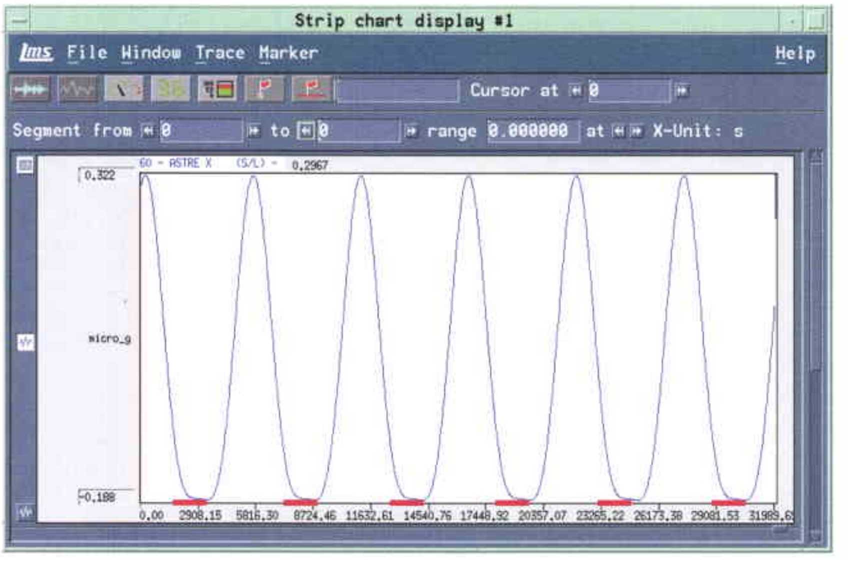


Figure 7. Extraction of the Quasi-Steady Component (QSC) by Kalman filtering. The data are downsampled from the original sampling rate of 300 Hz to 1 Hz, which reduces the amount of data while leaving the signal content between 0 and 0.5 Hz unaffected

automatic transmission of data when threshold values adjustable from the ground are exceeded.

The cooperation between the NASA Glenn Research Center and the MMA Team during the Spacelab missions proved to be of extraordinary value to the investigators of microgravity-sensitive experiments. In view of ISS operations, a common data pool with the NASA PI Microgravity Support (PIMS) Group and NASDA is the next logical step in order to achieve highly efficient PI support worldwide around the clock.

Acknowledgements

The authors express their appreciation for the continuous support and friendly cooperation by NASA colleagues from different Centres: Richard DeLombard, Kevin McPherson and Roshanak Hakimzadeh (NASA Glenn Research Center, formerly LeRC), who with their interest and in the spirit of scientific cooperation made possible the MMA flights and shared the scientific results of the microgravity data analysis of both the LMS and MSL-1 Spacelab missions; Kevin Zari, Juan Calero and David Nardino (NASA Kennedy Space Center), who not only supported MMA during the integration at KSC but also became active and helpful members of the MMA team during the mission operations at the POCC. A special mention of gratitude goes to ESTEC colleagues and team mates Massimo Bandecchi (MMA system engineer during the reflight activities) and Giancarlo Scaramelli. With their experience and dedication, they contributed significantly to the improvement of the GST, even during the missions.

ESA Payloads and Experiments on the Foton-12 Mission

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Introduction

The international Foton-12 mission was successfully completed in September 1999, carrying a range of scientific payloads and experiments developed and prepared under the supervision of ESA and the national space agencies of France (CNES), Germany (DLR) and Russia (RKA).

The international Foton-12 mission in September 1999 was a milestone in terms of payload mass, complexity and scientific diversity. ESA's contribution amounted to an unprecedented 240 kg – almost half of Foton's total payload. The Agency's 11 experiments covered fluid physics, biology, radiation dosimetry, materials science and meteoritics. This article describes the mission from an ESA perspective and highlights the initial results.

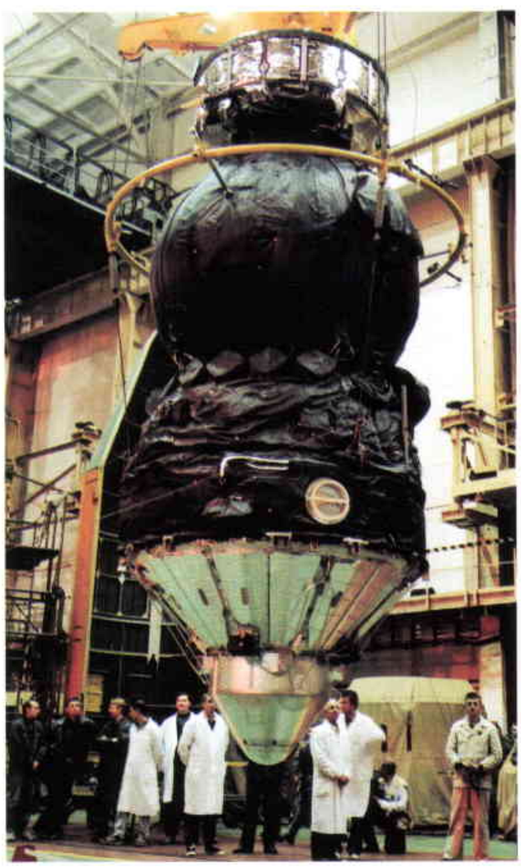


Figure 1. Foton comprises three principal sections: the battery pack (top), the spherical return capsule, and the service module (bottom)

The Russian Foton (Fig. 1) spacecraft was conceived to conduct experiments in weightlessness. It is designed and built by Russia's Central Specialised Design Bureau of the State Research and Production Space Rocket Centre ('TsSKB-Progress') and made its first flight in 1985. Launched by a Soyuz-U rocket, Foton consists of three sections: descent module; battery pack; and attitude and orbit control module. The descent module is a pressurised 2.2 m-diameter sphere housing the scientific payload. It is protected by a heatshield and is the only part of Foton to return from orbit at the end of the mission. The battery pack is the main energy source for the satellite and payload. The attitude and orbit control module is equipped with gas thrusters and a rocket engine used for the reentry burn. The landing system employs parachutes and a retro-rocket to cushion the landing impact. The payload is retrieved and returned to ESA personnel in Samara, Russia within a day.

Foton is capable of carrying a scientific payload of up to 500 kg, with an average daily power budget of 400 W (on a typical 2-week mission) and power consumption peaks of 700 W (for a few hours). The residual acceleration levels are 10^{-4}–10^{-6} g.

Foton-12 was launched on 9 September 1999 from the Plesetsk Cosmodrome, about 1000 km north of Moscow, entering a 225x405 km orbit with an inclination of 62.8°. It remained slowly rotating in space for 14.6 days before its descent module was commanded from the ground to reenter. It landed safely on 24 September in a desert region near the city of Orenburg in Russia, close to the Kazakhstan border. All the payloads were retrieved at the landing site and within a few days the experiment samples and the recorded flight data were made available to the investigator teams in the various universities and research institutes involved in the mission.

ESA has been using Foton and the Bion life sciences counterpart since 1987 for its microgravity experiments. ESA's Biobox and Biopan facilities, specifically designed for Bion/Foton, had each previously flown three times aboard these spacecraft. Foton-12 saw the debut of the complex FluidPac fluid physics facility and its TeleSupport Unit, in addition to the fourth flight of Biopan and three autonomous experiments.

ESA facilities and experiments

ESA's principal fields of scientific investigation on Foton-12, limited to space biology in past missions, extended to fluid physics and materials science. ESA's payload totalled 240 kg, the largest so far in this series of missions. ESA was also allocated 50% of the materials science experiments using DLR's Agat furnace.

FluidPac

FluidPac is a new-generation facility for investigating fluids in weightlessness. It was designed and built by Verhaert (Belgium); Alcatel-Space (Switzerland) and Kayser Italia (Italy) were subcontractors responsible for the data management system software and part of the electronics, the Microgravity Research Centre of the Université Libre de Bruxelles took care of the diagnostics concept and optics layout.

FluidPac is designed for observation and measurement of thermo-capillary phenomena along free liquid-gas interfaces. Other types of fluid physics experiments can also be performed. The reusable instrument offers multi-purpose diagnostics, and can accommodate three complex experiment containers (Fig. 2). The optical diagnostics include observation along three different axes; two Electronic Speckle Pattern Interferometers, for free surface deformation and transmitted modulation, respectively; and one Infrared Camera, working at 8–12 µm (Fig. 3). The fluid sample can be illuminated either by diffuse light or by two adjustable light sheets to make visible the experiment volume and to measure the velocity field in two orthogonal planes. The experiment containers are brought under test sequentially by means of a rotating platform. Experiments are executed automatically following pre-selected timelines, but they can also be partially controlled from the ground via the TeleSupport Unit (TSU). High-resolution digital cameras acquire the relevant images which are then stored as filtered Fourier coefficients, calculated by an Image Compression Algorithm.

The experiments require the application of thermal gradients. The boundary conditions on the cold side of each experiment are set by a

Table 1. ESA's payload on Foton-12

Facility	Mass	Experiments
FLUIDPAC	182 kg	BAMBI MAGIA
TELESUPPORT	24 kg	TRAMP
BIOPAN-3	27 kg	DOSIMAP SURVIVAL VITAMIN YEAST
Autonomous Experiments	4.5 kg 2.3 kg 0.2 kg	ALGAE SYMBIO STONE
Total mass	240 kg	

Figure 2. The three Experiment Containers installed on FluidPac's rotating carrousel, ready for flight

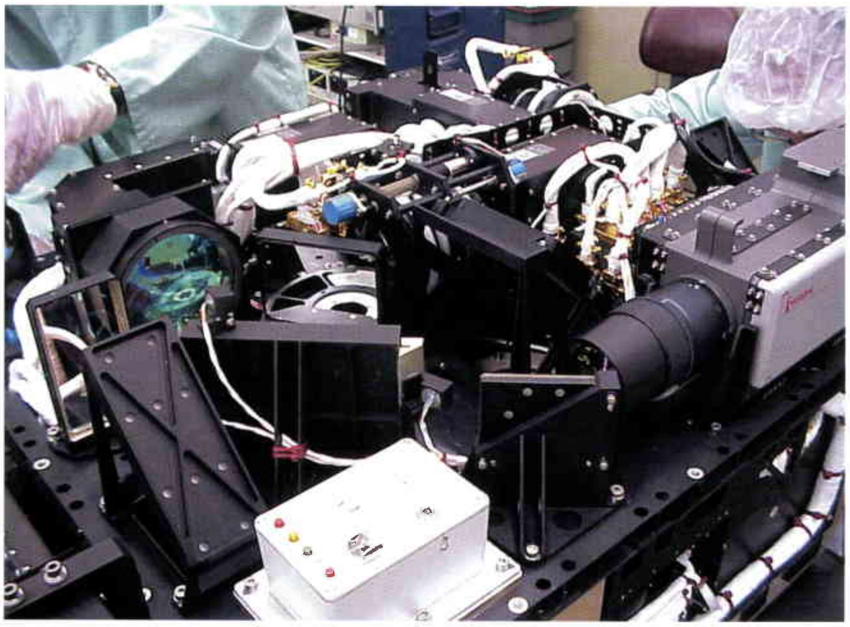


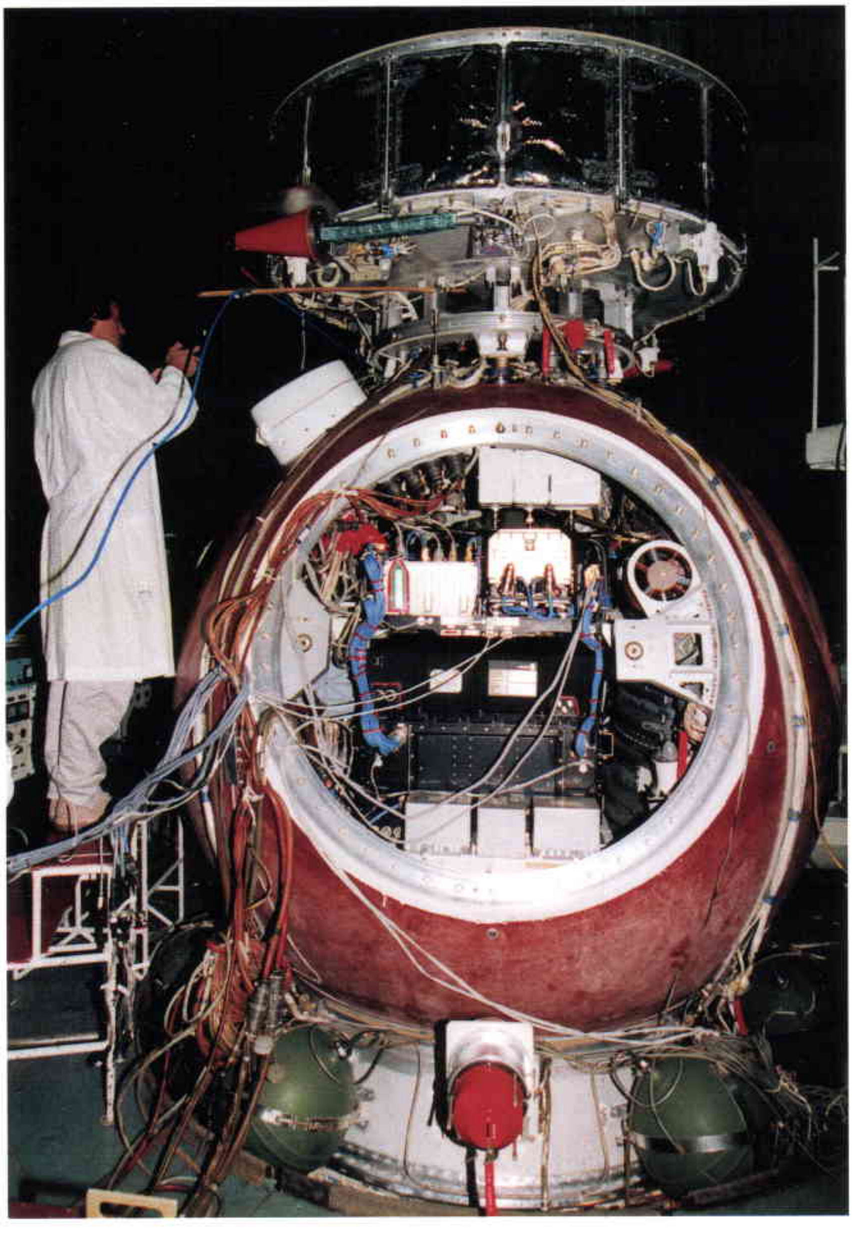
Figure 3. Fluidpac's optical diagnostic

thermal control loop, capable of removing up to 30 W net heat. The temperature on the hot side, directly adjusted within the experiment container itself, is regulated by a liquid loop. A hydraulic pump pushes pre-cooled water into the cold core of the active experiment container, removing the heat flux generated by the internal heater. At the end of the chain, the heat is released to the spacecraft environment through a set of Peltier elements, radiators and ventilators.

Table 2: FluidPac characteristics

Experiment Box mass	125.7Kg
Electronic Box Assembly mass	47.6 Kg
Experiment Box size (W,H,L)	800x560x940 mm^3
Electronic Box Assembly size (W,H,L)	825x345x715 mm^3
Handled Electrical Power (max.)	400 W

Figure 4. The FluidPac Experiment Box and the Electronic Assembly integrated inside the capsule during final preparations. The TSU deployable antenna (red) is visible below Foton's battery pack. The Algae, Symbio I and Symbio II Autonomous Experiments are in front of FluidPac



Fluidpac is composed of two different blocks: the Experiment Box and the Electronic Box Assembly, lying on the lower and upper part of the attachment structure, respectively (Fig. 4). FluidPac's main characteristics are given in Table 2.

FluidPac experiments

The experiments selected for FluidPac's maiden flight were Magia, Bambi and Tramp.

Magia (Marangoni-Grown Instabilities in an Annulus) was designed to investigate thermo-capillary flows, particularly their typical motions and structures, and their time-dependent behaviour. The basic thermocapillary flow is 2-dimensional with radial inward flow near the surface and radial outward flow near the bottom. As the Marangoni number increases, the single roll flow undergoes a transition to a multi-roll flow or to a 3-dimensional pattern. At even higher values, the multi-roll flows can undergo a transition to a time-dependent state. These three possible states are coupled to a characteristic deformation of the free surface and to the temperature distribution across it. Hence, the flow structures are studied by measuring the deformation and the temperature distribution of the free surface.

Bambi (Bifurcation Anomalies in Marangoni-Benard Instabilities) investigated the behaviour of convective motions near the threshold of instabilities occurring in a flat liquid layer when heated from below. The Bambi's primary objective was the determination of the critical Marangoni number M_{ac}, at which this instability effect is triggered. Secondary was the study of the near-threshold behaviour, with a quantitative gauging of the hysteresis, correlation length and growth constant. Surface deformations and velocity maps have to be recorded in conjunction with the injected power, after some thermal relaxation time. The transport of liquid changes its speed as a function of the heat flux and the distance from the lateral walls of the cell. Liquid flows can be made visible with the help of two CCD cameras observing the dispersed tracers from two perpendicular directions. Surface interferometer and IR observations of the free liquid surface are possible through the top window of the cell. The fluid sample is a silicone oil of 200 cS viscosity. The filling gas is helium, chosen because its thermal conductivity is almost the same as oil's. Thanks to this characteristic, the discontinuity in the thermal gradient at the liquid/gas interface is negligible.

Tramp (Thermal Radiation Aspects on Migrating Particles) applied a series of temperature gradients to solid particles suspended in a liquid solution, observed their movements and measured their drift velocities. The main goal was to prove the existence of thermal radiation forces acting in non-isothermal systems formed by condensed phases, and to measure their intensity. Thermal radiation forces have also been measured on molecules and ions, through the determination of the coefficients of thermo-diffusive drift of solutes, but the presence of a solvated layer around the solute particles and the fact that the wavelength of the impinging thermal excitations is comparable with the radial dimension of the particles, create complex diffraction phenomena. The size of the particles chosen for Tramp ranged from 100 µm to 1 µm, eliminating this problem.

The average speed of the particles is a function of their size, for a given gradient. Contrary to ground experiments, large particles are expected to move in orbit faster than the small ones. In a gravity-driven environment, in fact, the thermal radiation force, proportional to the cross section of the micro-sphere (hence to r^2), acts against two forces: the viscous force, proportional to the radius r of the particle, and the buoyancy force, proportional to its volume (hence to r^3). In weightlessness, buoyancy is strongly reduced, so the contribution of the heat flux force becomes more important as the particle cross section increases. Speeds of up to 1 cm/min have been measured on the ground in an isopicnic solution.

TeleSupport Unit (TSU)

FluidPac was provided on Foton-12 with the TSU telecommand and telemetry unit. TSU was designed and built by the Swedish Space Corporation (SSC) with Technosystem (Italy) as subcontractor responsible for the development of the Data Handling Unit (DHU). The DHU includes an enhanced image processing module capable of acquiring images and data, processing and compressing them with very high compression ratios and, finally, down-linking them to a ground station. This module has the task of acquiring data from the experiments (e.g. housekeeping data, sensor readouts and digital video) and storing a selection for pre-processing and transmission to the ground.

In short, the TSU's main function is to act as a relay between FluidPac and the ground station for both telemetry and telecommanding. This feature allows the FluidPac operators to update any of the experiment parameters, as well as some of the boundary conditions or the diagnostics configuration. In parallel, TSU can present 'mailed instructions' to FluidPac for immediate or deferred execution. This mode opens the door on increasing the scientific return from FluidPac's experiments.

The data link capability is made possible by a newly developed omni-directional antenna system and supporting radio frequency (RF) subsystem. These antennas with their conical-shaped radiating elements, designed and developed by TsSKB, were attached directly to Foton's battery module (Fig. 4).

Figure 5. Biopan is seen during its final installation onto Foton

Biopan

Biopan is a pan-shaped exposure facility designed and built under an ESA contract by Kayser-Threde (Germany), with Kayser Italia (Italy) responsible for the flight software and the operational Electrical Ground Support Equipment. It is designed to host exobiology, radiobiology and materials science experiments, aimed at evaluating the combined or individual effects of solar UV light, space radiation, vacuum, extreme temperatures and microgravity on biological samples, materials specimens and electronic components.

Biopan is mounted externally on Foton's descent module (Fig. 5), protruding through the thermal blanket that envelopes the satellite.

Power and data links are provided via cables that are stripped away by the separation of the satellite modules during reentry. Biopan also carries an internal battery to provide energy to its subsystems beginning with reentry.

Biopan's upper shell is a motor-driven lid that opens 180° in orbit to expose the experiment samples to the space environment. On Foton-12, the lid was opened 20 hours after launch, as required by one of the experiments. At the end of the mission, the lid is closed by a telecommand sent from ground, although a pre-programmed internal back-up command ensures closure in the event of communications problems. In normal operations, the lid remains open throughout the orbital phase and is closed shortly before reentry. To withstand the extreme heat during atmospheric reentry, the entire Biopan structure is protected by an ablative heatshield. The lid may also be closed in orbit for the safety of the facility and its closing mechanism if temperatures exceed the normal range.

Following a test flight in 1992, Biopan flew in 1994 on Foton-9 and in 1997 on Foton-11, each time carrying six experiments. On Foton-12, it hosted four new experiments.

Biopan's experiments

The experiments (Table 3) loaded in the lid plate and in the bottom tray (Fig. 6) were Yeast, Dosimap, Vitamin and Survival.

Yeast studied radiation damage in yeast cells and their interaction with space radiation. Although the biological effects of heavy radiation particles (HZE) on living organisms have been studied extensively, those of the softer components of the space radiation spectrum have not. Cultures of yeast cells were exposed under minimal shielding conditions (<11 mg/cm^2), allowing high dosages of electrons to be absorbed. Reference samples were kept shielded against electrons behind 0.5 g/cm^2. The preliminary results suggest that the viability of the electron-exposed samples was significantly reduced after flight. This may be the first demonstration of a biological effect caused by the soft component of the space radiation environment.

Dosimap was a dose-mapping experiment,

Table 3. ESA experiments flown on Foton-12

Short name	PI	Affiliation	Title	Science field
ALGAE	Prof. H. van den Ende	University of Amsterdam (NL)	Effect of microgravity on cell cycle kinetics in the unicellular green algae *Chlamydomonas*	Cell biology
BAMBI	Prof. J-C. Legros	Université Libre de Bruxelles (B)	Bifurcation anomalies in Marangoni-Benard Instabilities	Fluid physics
DOSIMAP	Dr. G. Reitz	DLR, Porz-Wahn (D)	Dosimetric mapping	Radiation dosimetry
MAGIA	Prof. D. Schwabe	University of Giessen (D)	Marangoni-grown instabilities in an annulus	Fluid physics
STONE	Dr. A. Brack	CNRS, Orléans (F)	Thermal processing of artificial sedimentary meteorites during entry into Earth's atmosphere	Meteoritics
SURVIVAL	Dr. G. Horneck	DLR, Porz-Wahn (D)	Survival rate of microorganisms exposed to solar UV	Exobiology
SYMBIO	Dr. L.G. Briarty	University of Nottingham (UK)	Plant-bacterial symbiosis in microgravity	Plant biology
TRAMP	Prof. F.S. Gaeta	MARS Center, Napoli (I)	Thermal radiation aspects on migrating particles	Fluid physics
VITAMIN	Dr. N. Dousset	Rangueil University, Toulouse (F)	Radiation effects and efficiency of radioprotectors on biological a-cellular systems in space	Radiation biology
YEAST	Prof. J. Kiefer	University of Giessen (D)	Radiation damage in yeast cells: interaction of space radiation components.	Radiation biology

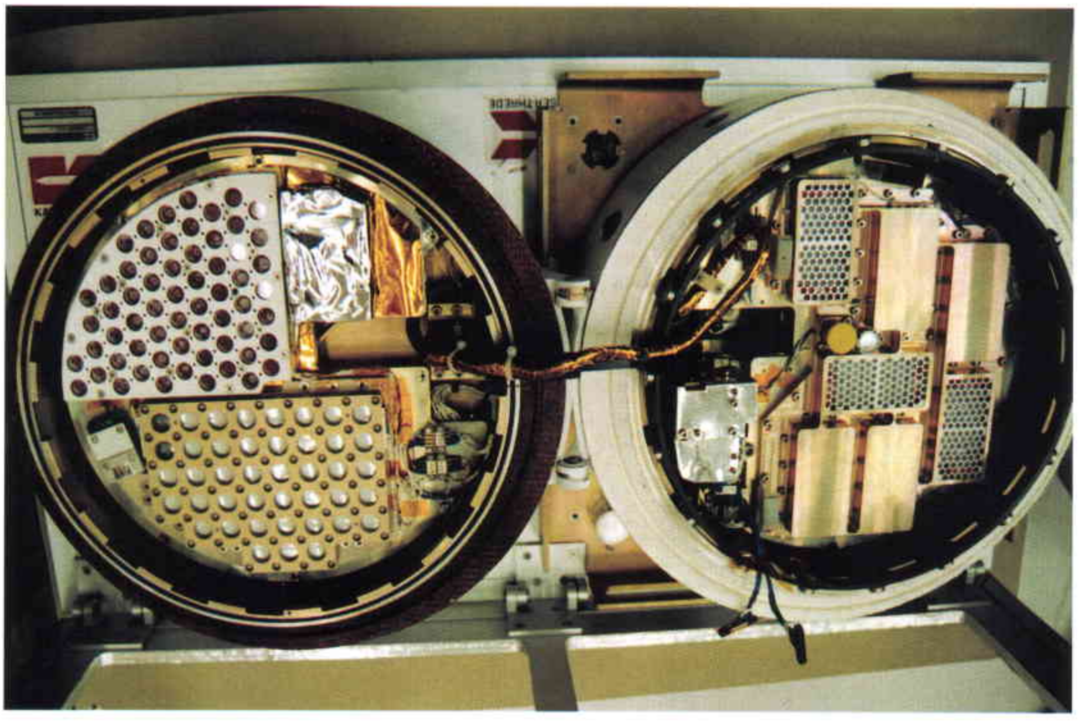


Figure 6. The Biopan experiments integrated on the lid (left) and bottom tray before installation of the thermal blanket. Survival is top left; Yeast is bottom left; Vitamin occupies most of the bottom tray

using a variety of radiation dosimeters to monitor the space radiation environment in low Earth orbit. Additional detectors were attached to FluidPac's body, for comparison with radiation doses outside of Foton.

Vitamin studied the radiation damage and the efficiency of radiation-protection materials on biological a-cellular systems in space. In a pioneering ESA experiment on Biopan-1/ Foton-9, evidence was produced that, firstly, large biological molecules in solution can be damaged by space radiation, and, secondly, that the damage can be countered by radiation-protection substances. This experiment was partly a repetition and partly an extension of the earlier study, which eventually may lead to the development of protective drugs against radiation.

Survival was aimed at measuring the survival rate of microorganisms exposed to the harsh space environment of vacuum, extreme temperatures, radiation and solar UV. Confirming and extending earlier results, evidence was found that bacterial spores and halophilic microbes can survive 2 weeks in open space. These data add credibility to the theory of panspermia – the possibility that simple life forms may travel from one planet to another on meteorites.

Autonomous Experiments

As on Foton-10/11, three 'passive' experiments were included. Two of them, Algae and Symbio (I & II), were contained in special boxes (Fig. 4), installed at a late stage (Launch-72 hours) inside the capsule. The boxes, always transported, pre- and post-flight, in thermally controlled conditions, had their own power supplies and data acquisition and storage. After landing, they were delivered to ESTEC and picked up by their investigators within 4 days.

Algae investigated how weightlessness affects the cell division cycle (cell size and proliferation rate) of the *Chlamydomonas* unicellular green alga. In orbit, the cells were grown for 4 days under continuous light.

Symbio investigated the symbiosis between higher plants (legumes) and nitrogen-fixing microbes in weightlessness.

Stone

In addition to the above biology experiments, a simple new passive experiment flew on Foton-12. 'Stone' investigated why, among the 14 known meteorites believed to have come from Mars, none is of sedimentary origin. A prime possibility is that they are altered beyond recognition by passage through the Earth's atmosphere, if they survive at all. Stone studied the physical and chemical modifications in sedimentary rocks during entry. Generally, meteorites differ from ordinary terrestrial rocks by the coloured fusion crust acquired during the journey through the atmosphere. However, carbonate-rich martian sedimentary rocks may never develop a fusion crust. Thermal decrepitation of carbonates during atmospheric infall is likely to produce a surface texture that is not recognisable as a fusion crust, in which case such meteorites would be overlooked by collectors. In addition, atmospheric entry may also alter the chemical and isotopic composition of the samples.

Three pieces of terrestrial rock (Fig. 7) were exposed to the rigours of atmospheric entry on the exterior of Foton-12. The first, a basalt, was intended as the inflight control to demonstrate that the entry heat is sufficient to form a dark fusion crust (although Foton's entry speed is lower than that of a meteorite). The second was a solid pure carbonate rock (dolomite) to verify the heat decrepitation and concomitant loss of mass during entry. The third was a simulated basaltic sediment modelled after the Mars Pathfinder findings: regolith-like with incomplete chemical weathering but with chemical hardening (pore space precipitation from carbonate and sulphate-rich groundwater). This sample was made in the laboratory of one of the co-investigators, Prof. G. Kurat from the University of Vienna (A).

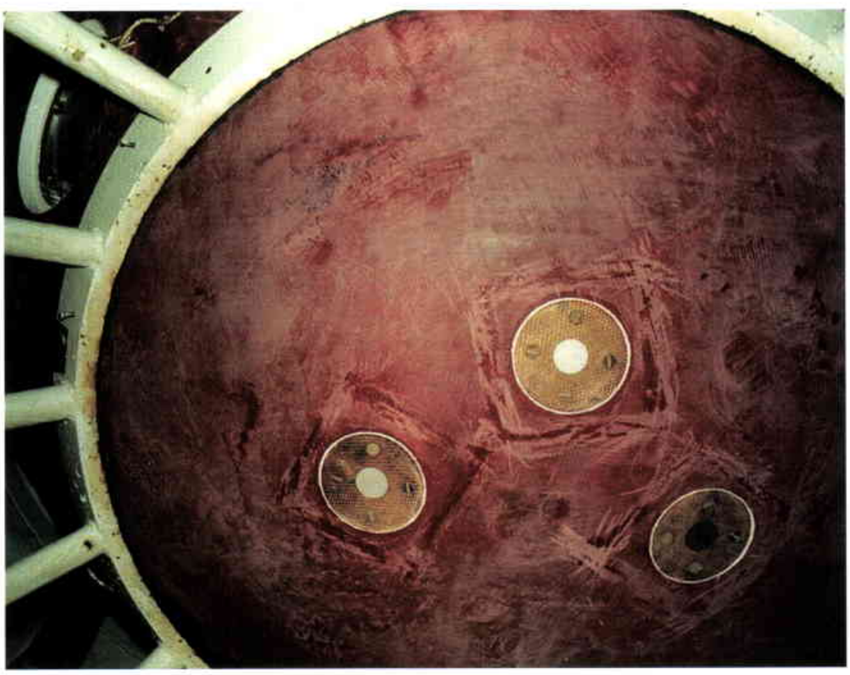


Figure 7. The three Stone samples installed on the Foton heat shield, close to its stagnation point. The simulated martian sample is at top

The physical and morphological aspects of the infall samples are being studied by the investigators. In addition, they are being analysed for their chemistry, mineralogy and isotopic compositions. In each case, the changes accompanying atmospheric infall are being referred to the original, untreated samples.

Operations

ESA's payload operations were driven by the requirements of the experiments. Four different phases can be distinguished, as outlined below:

Integration and test in Foton

This phase took place about 3 months before launch, at the TsSKB-Progress factory in Samara, where the Foton spacecraft are built. Samara is one of the largest industrial cities in Russia, about 1000 km south-east of Moscow. Named Kujbyshev in the Soviet era, it was a closed city until 1993 and only since the Foton-11 mission in 1997 have foreign personnel been allowed access to TsSKB to work jointly with Russian personnel during the satellite-payload interface tests.

Stone was the first experiment to go on board. In March 1999, the three rock samples were mounted on the descent module's exterior by means of special holders. They were attached close to the capsule's stagnation point in order to experience the greatest thermal conditions during atmospheric reentry.

After troubled preparations with Tramp, the only FluidPac experiment cell to be completely filled on the ground, the whole ESA payload reached Samara in mid-June 1999. TSU, FluidPac and Biopan were installed in sequence on Foton-12. Apart from some problems during the Biopan-Foton fit-check, all of the mechanical interfaces were successfully verified.

The work continued for 3 weeks, and included all the functional verifications, the validation of the electrical interfaces with the carrier and a number of sequences of combined system tests aimed at simulating some critical mission phases. The ESA instruments passed all of these tests smoothly except for a minor, but annoying, failure of a memory chip inside Fluidpac's Central Data Management System (CDMS). The failure was discovered only after test data were analysed, leading to the decision to swap the CDMS with its spare flight unit. However, this operation had to be delayed until the pre-launch operations at Plesetsk.

After completion of those tests, Biopan was removed from Foton-12, as planned, in order to allow the integration of the biological samples into Biopan at a very late stage at ESTEC. FluidPac and the TeleSupport Unit remained aboard Foton and left Samara on 23 July 1999 for the 2500 km-long train journey to Plesetsk along with the Soyuz launcher stages.

Pre-launch phase

This phase began 3 weeks before launch at the Plesetsk Cosmodrome. Plesetsk is a remote place in northern Russia, covering ~15 000 km^2 of birch and maple tree forest under the control of the Russian Army's Strategic Rocket Forces. They coordinated Foton-12's final tests and carried out all the work up to and including the launch.

An ESA team of 10 engineers installed the Bambi and Magia experiment samples in FluidPac, and checked out all the FluidPac and TSU subsystems. The samples were prepared a few days in advance and transported directly to Plesetsk as hand luggage. Mounting the detachable experiment fluid reservoirs was a difficult job because of the restricted access to FluidPac from the service platform. After replacing the faulty CDMS with its spare unit, a malfunction in one of TSU power boards was detected. The problem, caused by a manufacturing defect that worsened during the transfer to Plesetsk, eventually causing a short circuit, was at last identified and fixed, but the whole exercise delayed Foton's launch by 2 days.

FluidPac pre-launch operations were completed after purging Bambi's experiment container with helium and flushing dry air through its experiment box in order to reduce the humidity that could have affected the optical components. Once TSU was back to full working order, a rather important test had to verify the electromagnetic compatibility among the various onboard RF-units. For this test, the whole satellite was detached from its scaffolding, lifted by a huge crane and suspended in the middle of the MIK integration hall. The building's impressive size allows this test to be performed almost as in an open field. That successful test concluded our verifications with Fluidpac and TSU, and ended any further contact with them before launch.

Biopan and the Autonomous Experiments had to be installed at the last possible moment. Both contained live biological samples, including yeast cells, spores, microorganisms and plants that are sensitive to temperature variation, humidity and ageing, and needed to be prepared in well-controlled environmental conditions shortly before launch. They were readied in the investigators' laboratories up to 8 days in advance and delivered to ESTEC in thermally-controlled containers. The exposure experiments were eventually integrated into Biopan just a week before launch, in ESTEC's cleanroom. A second ESA team carried these payloads from ESTEC to the launch site at L-4 days, flying on a special Russian Antonov-74 charter aircraft from Rotterdam, via Moscow, to Plesetsk. Housed in battery-powered special thermal containers until the last minute, they were installed in the capsule at L-3 days, 1 hour before the final closure of Foton's hatches.

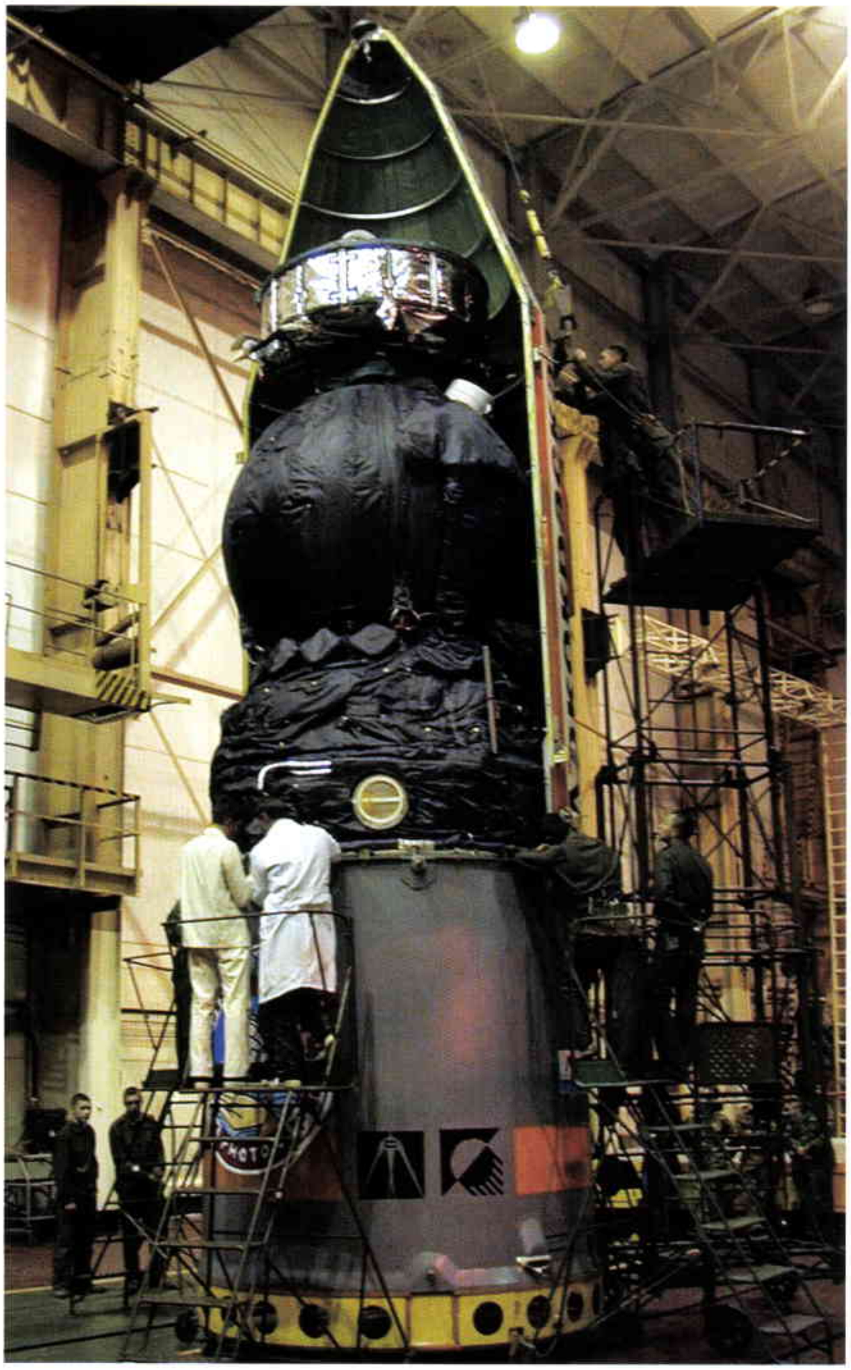
Biopan returned to its position on the capsule's exterior but, actually, it had to be installed twice because of a malfunction in its lid-opening subsystem that required additional repair work on the bench. Following a hard night's work, Biopan was installed with only a few minutes remaining before the deadline.

The following night, at L-2 days, the 6.5 t Foton was integrated with its Soyuz launcher. It was lifted from its supporting stand, gently lowered into the fairing coupling adapter and enclosed by the nosecone half shells (Fig. 8). This assembly was rotated to the horizontal and coupled to the rocket's third stage. The well-trained Russian personnel then added the combined first and second stages. The whole process took them only 8 hours, with a disarming routine and high efficiency, giving a demonstration of competence and skill.

On-orbit

We could follow the spectacular lift-off on 9 September until the 305 t Soyuz disappeared into a thick cloud layer. Nine minutes after leaving the launch pad, Foton-12 began its 234

Figure 8. Foton-12 almost ready for integration onto its Soyuz launcher. Biopan is the white cylinder at top right



orbits. A picture of the launch, sent directly from Plesetsk via an Inmarsat mobile phone, was displayed the next day on the computer screens of all those close to the project.

A few days before launch, a team of operators from ESA and industry had set up two Telescience Work Stations at Esrange, a complex of satellite-tracking stations (and the main European launch site for sounding rockets), about 80 km north of Kiruna in Sweden. Its location at 68.2°N, just above the Arctic Circle, was particularly favourable for tracking Foton. We could establish four 4-5 min contacts daily with Foton-12 thanks to the 13 m parabolic dish that captured the RF-signal beamed down by the two TSU antennas.

During the active phases of their experiments, the FluidPac investigators were at Esrange and followed their experiments from the Telescience workstations. At the same time, the received scientific data were deposited in a public Internet server physically located in the Royal Academic Institute of Stockholm. The other scientists and co-investigators, at their home institutes, could download those data directly to their personal computers, equipped with the right software. This link worked well and the transfer was smoother than expected.

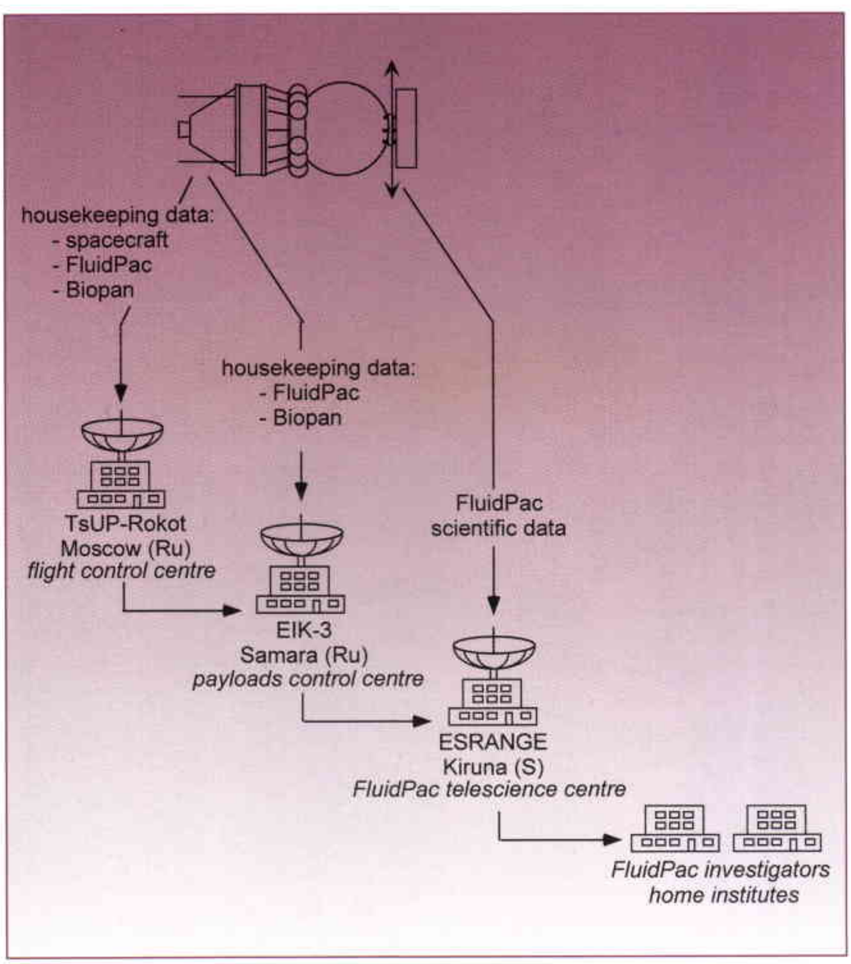


Figure 9. ESA's Foton-12 ground station network

While Esrange monitored the FluidPac experiments, the spacecraft itself was controlled from TsUP-Rokot, the Flight Control Centre in Moscow, and the payload's performance was monitored and analysed at the EIK-3 Payload Operation Centre in Samara (Fig. 9).

These different links also allowed a rapid exchange of information and requests for changes in the experiment timelines. There was also a special link with an FTP-server at ESTEC that was used to update a homepage reporting the day-by-day evolution of the Foton-12 mission.

FluidPac started operations, as planned, 22 min after Foton entered orbit. The first experiment, Magia, ran smoothly for its first 22 steps, but then a communication problem between two of FluidPac's subsystems stopped its execution. However, thanks to a telecommand from TsUP, the system was restarted and Magia continued according to the pre-programmed timeline.

The second experiment, Bambi, could not be performed because of a malfunction in the valve between the oil reservoir and the cell. The cause is still under investigation.

The third experiment, Tramp, then started automatically much earlier than expected because of Bambi's cancellation. This early start caused Tramp some problems, but the ground team at Esrange managed to interact with the facility and uplink parameter tables steering the experiment sequence back on course.

Although FluidPac suffered some malfunctions, TSU worked very well and allowed the investigators to check the status of their experiments from the ground by analysing selected images and other science-relevant data. It also proved to be a very useful troubleshooting tool and its use will surely be extended and optimised for future missions.

Biopan was a complete success. The lid opened as planned and was closed by a TsUP-Rokot telecommand about 30 h before landing. The experiment samples were exposed to the space environment for 12.6 days.

Telemetry received at TsUP-Rokot and EIK-3 showed that all the main parameters, including the lid position and the power and energy budgets, were normal throughout the flight. Other Biopan data from sensors close to the experiment hardware, including temperature sensors, a radiometer and an UV meter, were

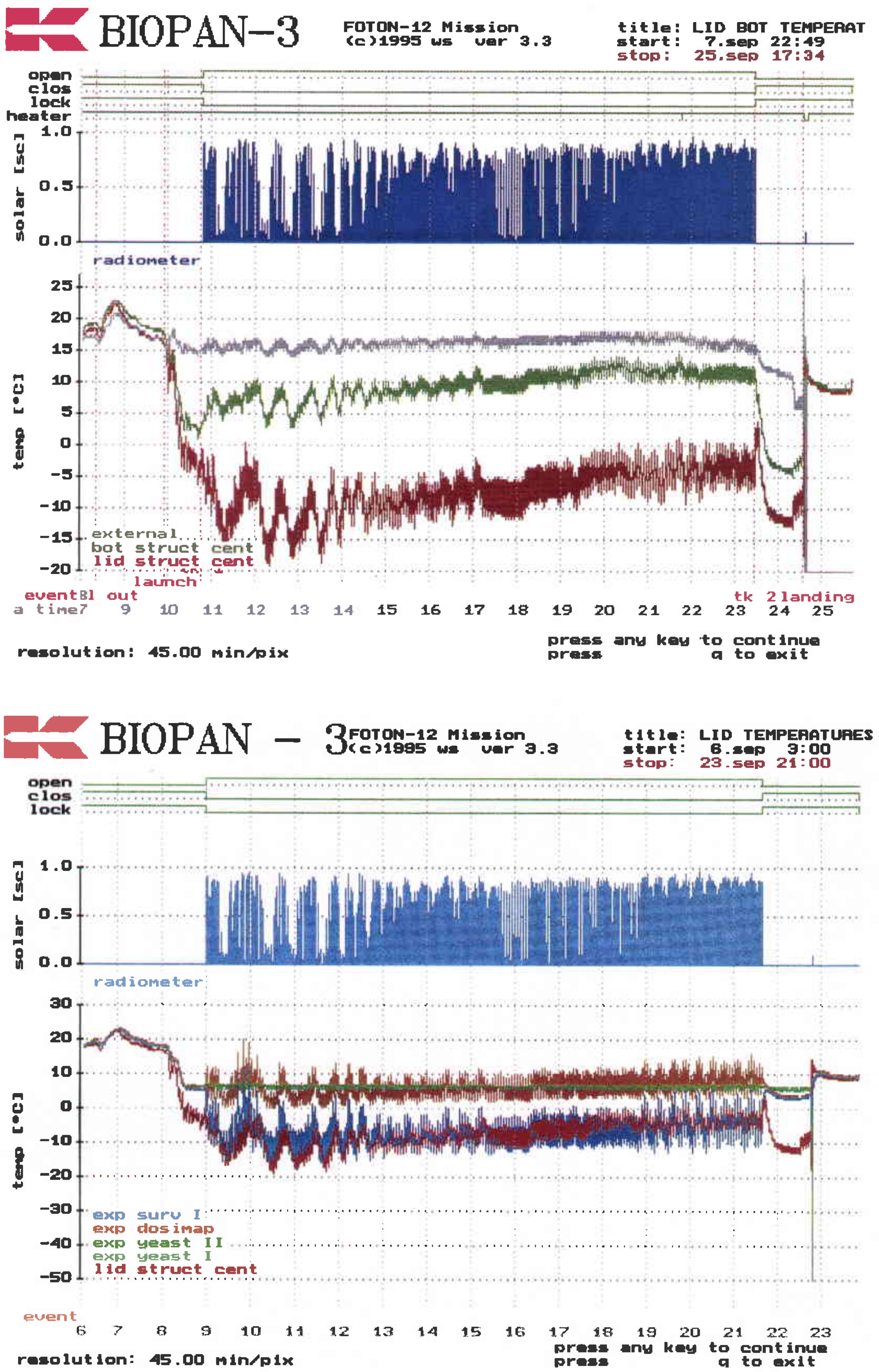


Figure 10. Readout of the Biopan sensors during flight. The upper (blue) display of both panels shows the output from Biopan's solar radiometer, reflecting the orbital period and Foton's slow rotation. The top panel includes temperature readouts from Foton's skin (silver, showing how well the spacecraft's multi-layer insulation maintained an even temperature), Biopan's bottom tray (green), and Biopan's lid (red). The bottom remained warmer than the lid because one side was attached to Foton. Both warmed up as the mission progressed because, as the radiometer shows, the time spent in sunlight increased. The temperature stability of the experiments is reflected in the traces in the lowest section. Yeast (green) and Dosimap (orange) were in Biopan's base, while Survival (blue) was in the lid. The red trace is again the temperature, as in the top diagram, but to a different scale

stored onboard and immediately downloaded after landing. They are now being analysed; a first quick look shows that the temperature control of the experiment worked beyond expectations (Fig. 10). We are now eagerly waiting for the full scientific results of the experiments.

Landing and post-landing

The satellite was deorbited when its ground track allowed a landing within Russian territory. Foton-12 touched down in the dry steppe about 130 km north-west of Orenburg on 24 September 1999, at 15:17 local time. The coordinates were 52°28′N, 53°50′E. The capsule, suspended from its parachute, impacted the ground with a measured shock of 38 g, but none of ESA's equipment suffered any damage (Fig. 11). An ESA team was at the landing site and retrieved FluidPac's Digital Tape Recorder (which carried all the scientific images and flight data obtained during the mission), Biopan, a set of dosimeters attached to FluidPac's body, and the Autonomous Experiments, including the burnt Stone samples. Unfortunately, the basaltic Stone sample and its holder were missing (Fig. 12). The other two were covered by a black burnt 'crust' and were immediately delivered to one of the investigators, at the landing site.

Figure 11. Foton-12 capsule recovery

Figure 12. The three Stone samples after landing. The basalt (top) and its holder were lost

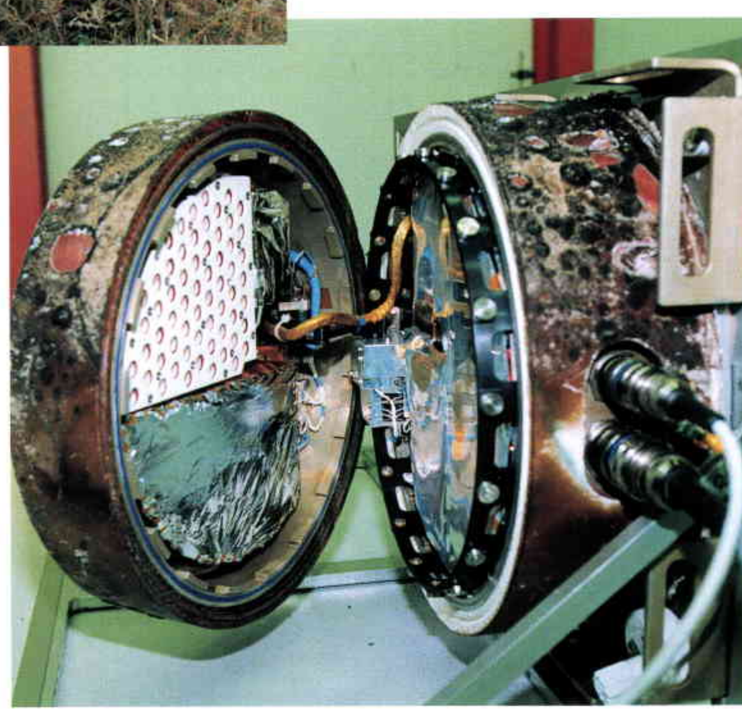


Figure 13. Biopan was opened in the ESTEC cleanroom on 27 September and the experiments removed for return to their investigators

Biopan and the Autonomous Experiments Algae and Symbio were placed in cooled transport containers and carried back to Samara the next morning. Finally, we brought them back to ESTEC on 27 September, again aboard the AN-74 aircraft. Biopan was then opened in the ESTEC cleanroom (Fig. 13) and the individual experiments handed back to their investigators.

Conclusions

From a preliminary analysis, Foton-12 can be considered to be a successful mission for ESA's experiments. All of the onboard ESA equipment, retrieved after almost 15 days in orbit, is in good condition and able to fly again.

Biopan and the Autonomous Experiments performed as expected, with no in-flight failures, and we hope the experimental results will confirm a 100% success.

FluidPac's scientific output was affected by the loss of Bambi. The other two experiments were conducted successfully, albeit with some problems. The science results await the analysis in the coming months of the data and images stored in FluidPac's tape recorder.

TSU proved to be a very useful tool for this type of mission. The need for more extensive ground coverage is the main lesson learned from its maiden flight on Foton-12.

Acknowledgements

The authors would like to thank V. Abrashkin and all the members of his team at TsSKB for their availability and flexibility in coping with the demands of our payloads, as well as ESTEC's J. Vago, M. Rieschel, H. Thoma, R. Bureo, Mrs M. Gotuvaya and J. Wissemburg for their instrumental contribution to the project. We are particularly grateful to Mrs T. Suslova and A. Fournier-Sicre, both with ESA-Moscow, and to Mrs H. Binck (ESTEC) for their helpful and devoted support, to all of the ground staff at Esrange, and to M. Incollingo (ESRIN) for the setting up and maintenance of the data network. We are also indebted to the industry project managers, engineers and technicians who took part in the Foton-12 mission, since their efforts went far beyond their contractual obligations. The success of the mission also reflects the continuous support and encouragement received from W. Riesselmann, W. Herfs, H. Martinides and W. Jansen, colleagues past and present.

Further Reading

Further information on the Foton-12 mission can be obtained via the web site <http://www.estec.esa.nl/spaceflight/index.htm> or by contacting the authors of this article.

The X-38 and Crew Return Vehicle Programmes

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In a highly successful partnership, NASA, ESA and European industry are building the X-38 spacecraft, the prototype of the International Space Station's Crew Return Vehicle (CRV). ESA is responsible for 15 X-38 subsystems or major elements, plus engineering expertise. Subscriptions by ESA Member States to the CRV programme will allow significant participation in the development and production of this next manned spacecraft. The X-38 and CRV are a quantum leap for Europe in developing and validating key reentry technologies and system designs needed for reusable space transportation systems.

Introduction

The X-38 programme is a multiple-application technology demonstration and risk mitigation programme, finding its first application as the pathfinder for the operational Crew Return Vehicle (CRV) of the International Space Station (ISS). It is using a rapid development approach through the incremental design, build and test of essential systems and technologies, and it represents new ways of reducing the cost of developing manned spacecraft by an order of magnitude.

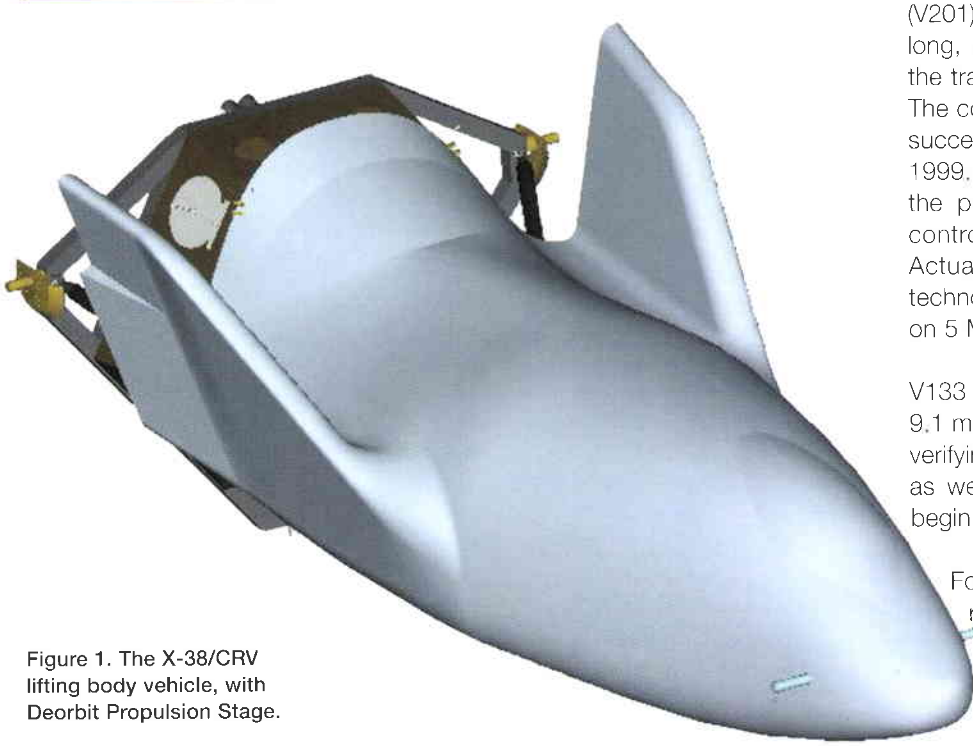


Figure 1. The X-38/CRV lifting body vehicle, with Deorbit Propulsion Stage.

The basic X-38/CRV configuration also offers inherent capabilities for other roles in the future, such as alternate access to space or as an in-orbit ferry to other vehicles (Crew/Cargo Transfer Vehicle (CCTV) or Space Taxi).

The X-38 is a lifting body with a disposable deorbit propulsion stage. This lifting body adopts the heritage of the US X-23/X-24 vehicles developed and flight tested in the 1960-70s, but it is enlarged and its shape has been significantly modified by ESA to improve the flying characteristics and volumetric efficiency. This design's entry crossrange capability allows a short orbital flight duration to assure a landing at specific ground sites irrespective of the time of departure from the ISS. The short orbital flight results in simpler, more reliable vehicle systems.

The X-38 programme is using four prototypes: three atmospheric drop-test vehicles (V131, V132 and V133) and a spaceflight test vehicle (V201). V131 is an X-24-shaped vehicle, 7.32 m long, with the primary goal of demonstrating the transition from lifting body to parafoil flight. The control surfaces are fixed. The vehicle flew successfully on 12 March 1998 and 6 February 1999. V132 is similarly shaped and scaled, with the primary goal of demonstrating the flight control systems using Electro Mechanical Actuators and advanced control software technology. V132 was successfully flight-tested on 5 March 1999 and 9 July 1999.

V133 will have the modified shape scaled to a 9.1 m length, with the primary objective of verifying the aerodynamic shape modifications as well as the control laws. Construction will begin this year.

Following its two flights, V131 has been refurbished to reflect the modified CRV shape, including the berthing/docking mechanism on the top. This V131R will resume flight testing early this year.

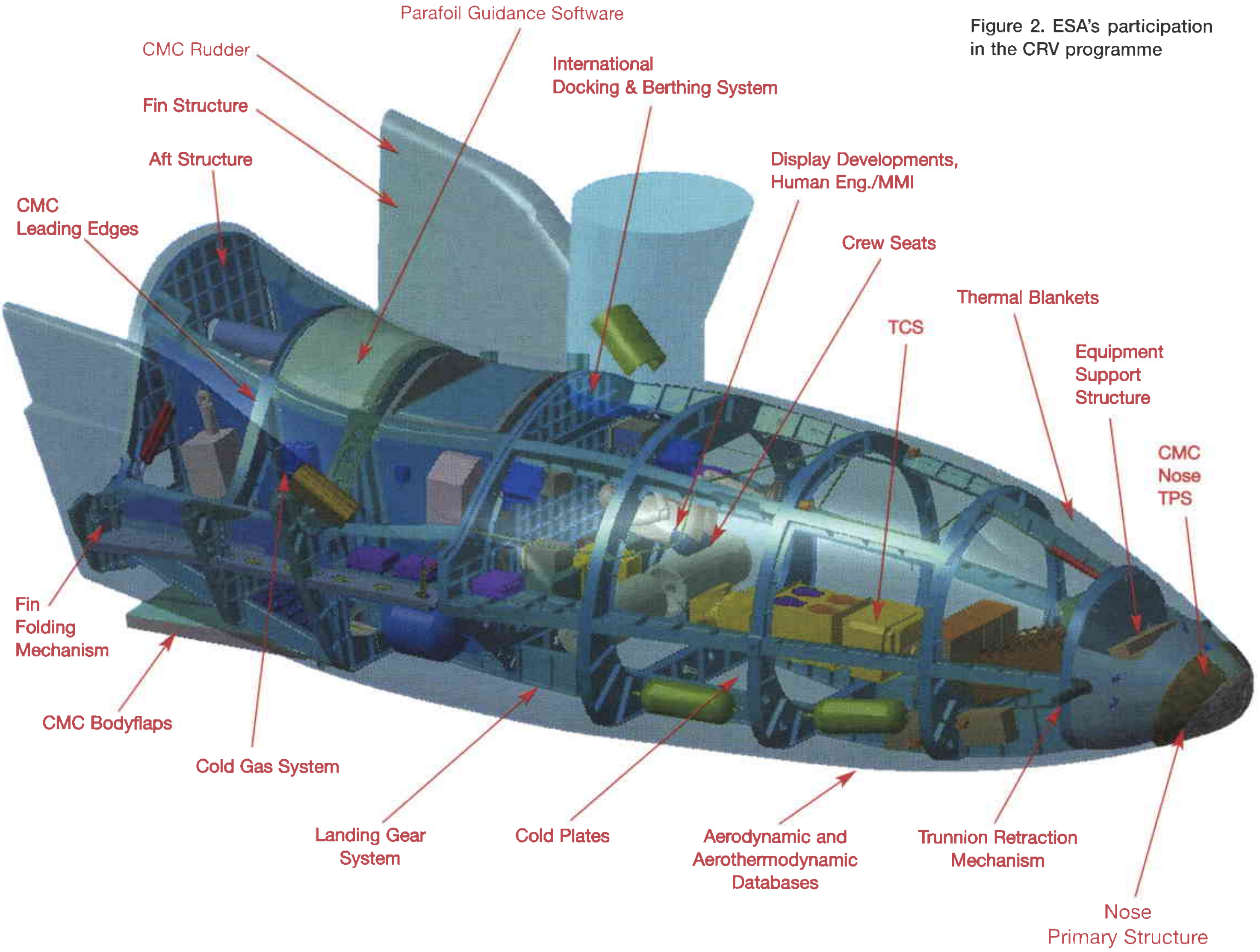


Figure 2. ESA's participation in the CRV programme

V201 is the spacecraft, to be deployed from Space Shuttle *Columbia* in early 2002 for a full-up entry test. It has the modified shape scaled to 9.1 m. In order to fit into the Orbiter's cargo bay, the upper parts of the fins are foldable. The deorbit propulsion stage is attached to the fuselage's aft frame. V201 is under assembly at the NASA Johnson Space Center – the primary structure is almost complete, the cabin has been successfully pressure tested and cabin equipment pallets have been installed.

Scope and objectives of ESA's participation in the X-38 programme

Initially a NASA in-house project, the X-38 programme developed into a full partnership between ESA and NASA: ESA is responsible for the design and development of 15 major subsystems or elements of the V201 spacecraft. ESA's X-38 programme is being performed under a firm fixed-price contract with MAN-Technologie (D) leading a team of 22 industrial companies in eight countries. ESA's X-38 contributions include:

- vehicle shape validation and overall aerodynamic and aerothermodynamic database;
- crew cabin design and layout;
- aft fuselage design and manufacture of major aft structure elements;
- rudders, including accompanying sensors;
- the metal nose structure;
- the front and main landing gear;
- the cabin equipment pallets;
- hot structure (Ceramic Matrix Composite, CMC) leading edge segments of the fixed fin, including accompanying sensors;
- the Thermal Protection System (TPS) blankets for the leeward vehicle surfaces, including fins and aft fuselage frame;
- guidance, navigation and control (GNC) software, including man/machine interfaces, for the parafoil flight phase;
- Fault Tolerant Computers with reentry GNC software;
- Vehicle Analysis and Data Recording System (VADRS), including front-end electronics for overall vehicle instrumentation;
- predevelopment of the CRV/ISS berthing/docking mechanism;
- active thermal control water pump;
- crew seat concept for the CRV and provision of a representative crew seat with instrumented dummy for X-38 flight testing.

In addition, ESA is providing engineering expertise related to CRV/ISS interface requirements definitions, avionics architecture integration, software validation, thermal control/environmental control and life-support system computer modelling, human interface concept development, independent flight control law simulation, vehicle integration and test support.

NASA, in addition to its subsystem responsibilities, is performing overall X-38 vehicle system engineering and integration, will launch V201 on the Space Shuttle and will deliver flight data for postflight analysis and assessment.

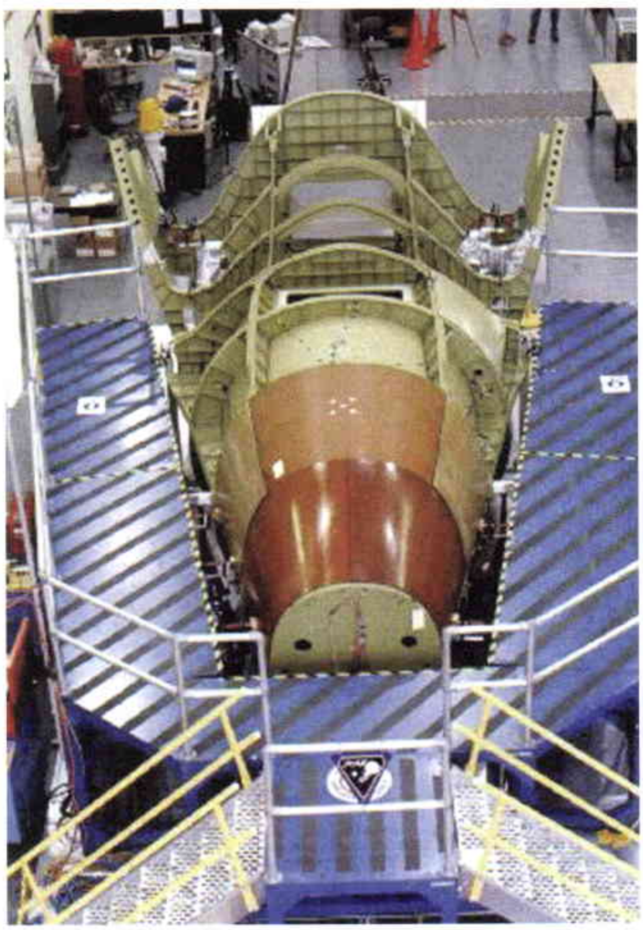


Figure 3. V201 under assembly at NASA's Johnson Space Center

The major European objective for cooperating with NASA on X-38 was to establish a clear path through which key technologies needed for future space transportation systems could be developed and validated at affordable cost and with controlled risk. The significant technical knowhow of Europe used in and gained through this programme can be applied to ESA's Future Launcher Technology Programme (FLTP) and beyond.

Atmospheric reentry is one of the key technologies that have to be mastered for future cost-cutting reusable space transportation. In this context, and specifically in relation to FLTP, the X-38 and the CRV programmes focus on access-to-space technologies.

The ESA/NASA partnership in the X-38 programme is complemented by DLR's TETRA (TEchnologie für zukünftige Raum-TRAnsportsysteme) programme, which is developing essential V201 elements, specifically the CMC body flaps and the CMC nose cap assembly. The complementarity of these programmes is reflected in a trilateral exchange of letters between ESA, NASA and DLR.

The X-38 programme will provide Europe with validation of essential designs and technologies for reusable reentry vehicles through a full-up spaceflight, reentry and landing demonstration of V201 in early 2002.

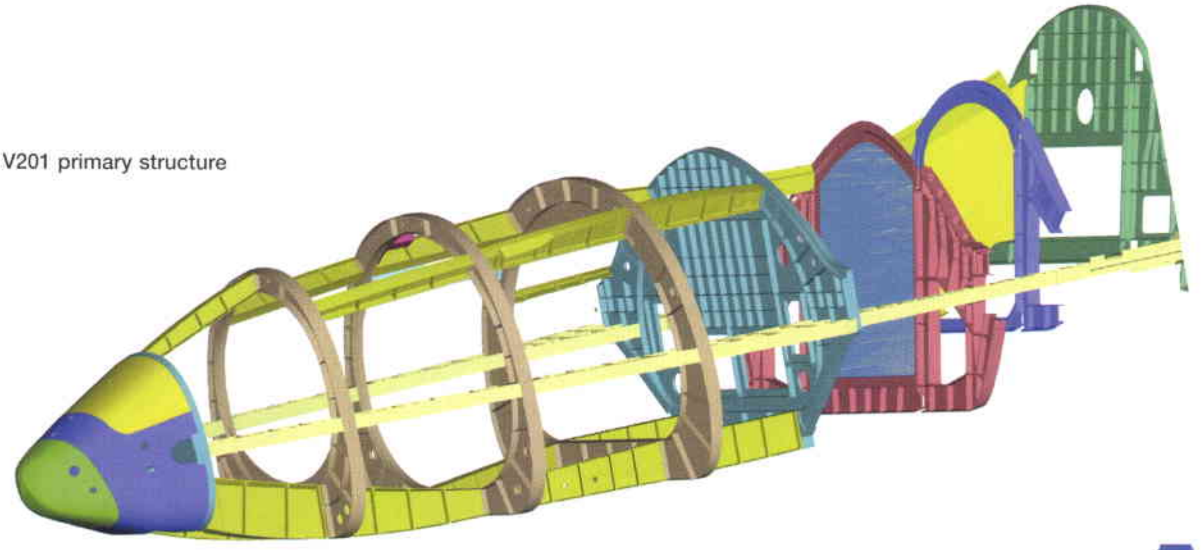
The X-38 cooperation is unprecedented. It is the first time that NASA, ESA and ESA contractors together are developing the prototype for a reusable operational spaceplane. The development of essential systems and technologies for a reusable, reentry vehicle is a first for Europe, and sharing the development of an advanced reentry spacecraft with foreign partners is a first for NASA.

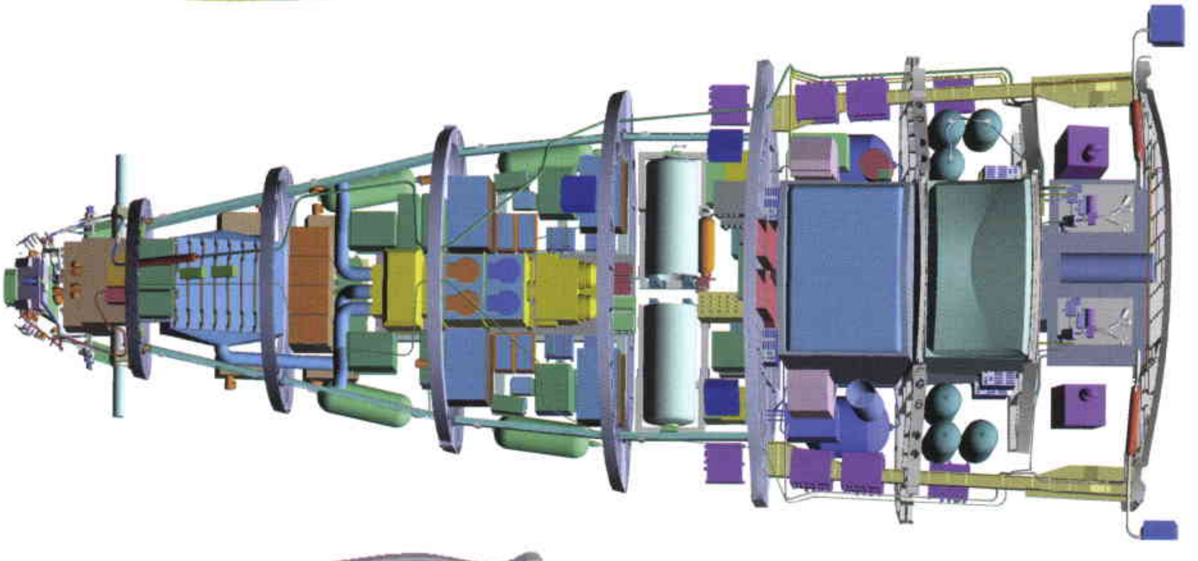
The full cooperation has been incrementally developed in a very short period, following the early success of ESA in significantly improving and visibly modifying the overall aerodynamic shape.

During the last two years, 22 Preliminary Design Reviews and Critical Design Reviews for the ESA elements have been successfully held. The last two CDRs (nose structure and V201 crew seat) were completed in July 1999. All hardware and software elements are in detailed design, development and manufacture. Major hardware (aft structure) was integrated into the flight model in late 1998, and all activities and planned deliveries are on schedule.

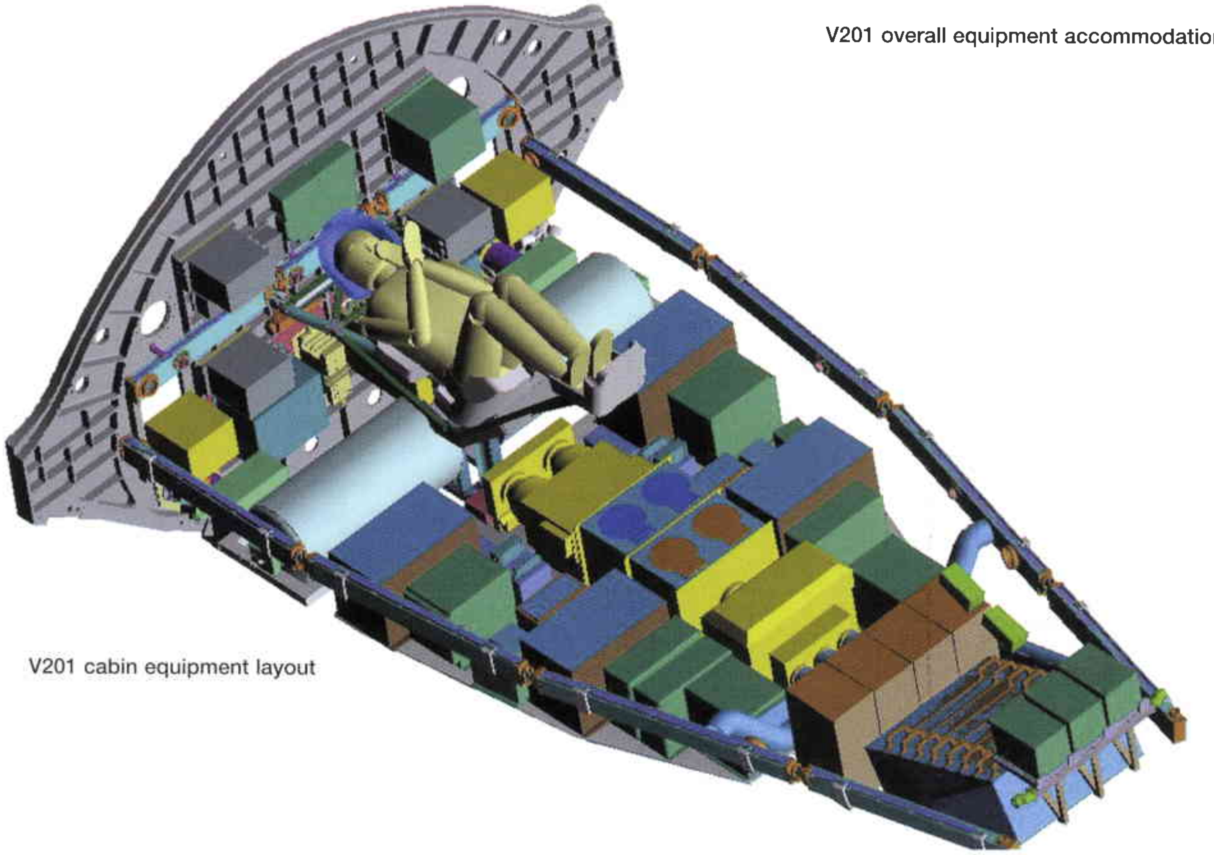
The programme's fast pace would not be possible without effective decision-making processes and the collocation of industrial partners in Europe and at NASA's Johnson Space Center (JSC). ESA's X-38 team includes engineers from 11 industrial firms working in an integrated team at JSC.

V201 primary structure





V201 overall equipment accommodation



V201 cabin equipment layout

The prototyping process leads to lower cost for the operational vehicles. Low-cost prototypes are being used to test key design issues before CRV production begins. Unpiloted tests allow greater risk-taking; atmospheric test vehicles are used to the maximum extent before going to space; materials and processes are used to design and build low-cost structures rapidly; modern software technology reduces the cost of ground and flight software development to support multiple vehicle configurations. The prototypes are used to establish the true requirements and identify any problems associated with the design concepts early on.

The V201 space test vehicle will fly the entire operational entry mission (speeds, altitudes, attitudes) of the operational CRV. Much of this flight regime has valid data from the three X-23 space tests, and once below Mach 2 and 25 km altitude we are operating in the X-24 database (28 flights). The ESA-provided aerodynamic and aerothermodynamic databases for V201, established through wind-tunnel testing and computational fluid dynamic (CFD) analyses, take into account the shape differences between the X-23/X-24 and the CRV. When the V201 spacecraft enters the subsonic region, it will be flying the same trajectory that atmospheric vehicles have flown many times. Once the drogue parachute is deployed and has decelerated the vehicle, the rest of the flight will be operating under the same conditions as all large parafoil deployments in the atmospheric vehicle and pallet drop-test programmes (approximately 90 tests). These tests initially use a 485 m^2 parafoil and later the full-size 680 m^2 parafoil.

Figure 4. Landing of X-38 V132 on 5 March 1999 (NASA)

Modern technologies enable a rapid prototyping approach: computer modelling tools in structures, aerodynamics (CFD), flight controls (Matrix X); low-cost data acquisition and instrumentation, to allow rapid test software development; extensive use of flight-qualified commercial off-the-shelf (COTS) equipment; and computer-aided design, manufacturing, laser inspection and software engineering.

These methods and processes, together with a lean management in ESA, industry and the interface processes with NASA, allow ESA to achieve the project objectives in a short time at very low cost.

The Crew Return Vehicle (CRV)

The ISS needs a CRV to support three missions: medical return, return of the crew if the Station becomes uninhabitable, and return of the crew if the Station cannot be resupplied.

The CRV has three main elements: the lifting body entry vehicle, the CRV/ISS international berthing/docking module and the deorbit propulsion stage. A total of four CRVs and two berthing/docking modules will be built.

Soyuz will provide the initial crew-return capability. While Soyuz has many limitations, it is considered acceptable for a limited time.

The CRV will be delivered by the Space Shuttle and remain attached for up to 3 years. It will accommodate from 0 to 7 crew members in a shirtsleeve environment, and be capable of autonomous flight operations and landing. The maximum mission duration (for an emergency departure) is 9 h, and about 3 h in the case of a medical return, which would allow time for optimum sequencing between ISS departure and reentry burn. The CRV must be able to separate from the Station at any attitude with a tumbling rate of up to 2 °/s. The maximum sustained entry *g*-load will not exceed 4 *g* along the longitudinal axis.

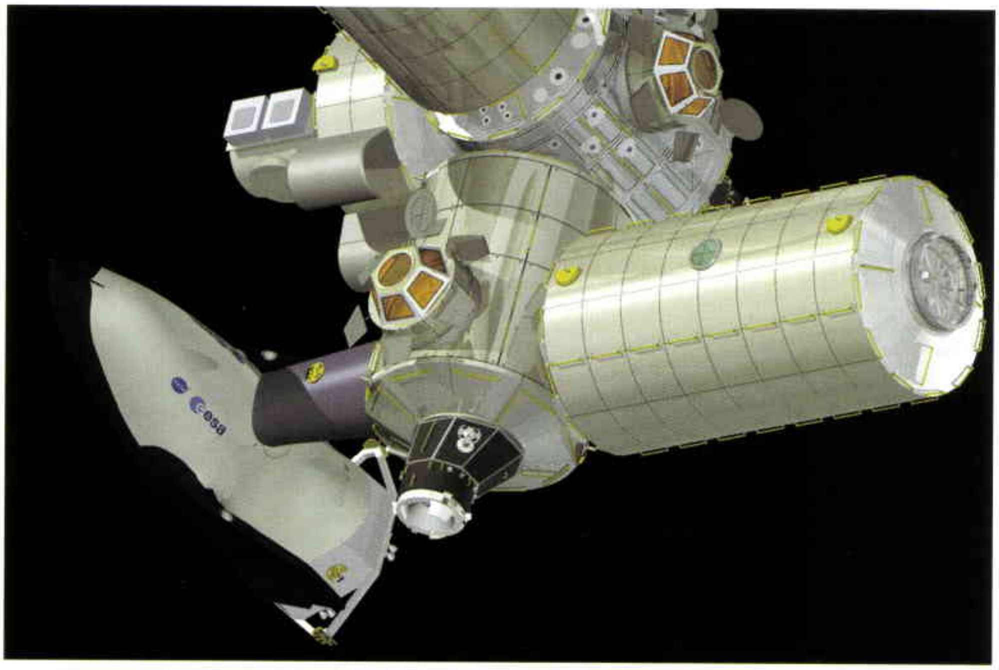


Figure 5. The CRV will remain attached to Node-3 for up to 3 years (ESA/D. Ducros)

Like the X-38 V201, the CRV will have a total length of 9.1 m and a cabin volume of 11.8 m^3. The landing mass will not exceed 10 000 kg. The landing accuracy will be ≤9 km radius and the landing speed ≤9.1 m/s horizontally and ≤4.6 m/s vertically.

ESA's participation in the CRV programme
ESA and NASA agreed in 1997 that it would be mutually beneficial to extend the X-38 partnership to the CRV. These early agreements at programme-management level were followed up by the NASA/ESA Protocol on X-38/CRV Cooperation, signed in November 1998.

At the May 1999 ESA Ministerial Conference in Brussels, it was decided to link a European contribution to the CRV programme with ESA's ISS exploitation phase committments. Following ESA's detailed programme proposal to the Manned Space Programme Board, confirmed and expected contributions by Belgium, France, Germany, The Netherlands, Italy, Spain, Sweden and Switzerland are substantial.

The scope of the participation will go beyond the X-38 partnership and will include additional major subsystems or elements, like the novel international berthing/docking system, fin folding and trunnion retraction mechanisms, display technique development, independent software verification and validation, cold plates, crew seats and the cold gas attitude and orbit control subsystem.

ESA will also be responsible for system engineering analyses, interface management for ESA elements, assemblies or subassemblies and integration or pre-integration of vehicle assemblies.

The ESA commitments are reflected in NASA's Request for Proposal (RFP) for the Phase-C/D of the CRV programme, which was released on 22 November 1999.

Early activities of the first phase of the CRV Phase C/D have started. Phase 1 will be completed shortly after the Critical Design Review, scheduled for August 2002. Phase 2 will start in October 2002, and will cover the production of four vehicles, ending in 2006.

Building on the considerable knowledge and experience of the X-38 industrial team, ESA is transitioning from the X-38 Phase C/D into the CRV Phase C/D, with the two programmes overlapping by about 2.5 years.

ESA's major participation in the CRV programme will ensure that the technologies and systems expertise needed for future space transportation systems will already be validated in an operational programme. The envisaged CRV production flight test will precede any European demonstration programme resulting from FLTP studies. This flight test will be an autonomous, zero crew, return of the first CRV flight unit when it is replaced by the second vehicle.

ESA issued the Statement of Work (SOW) for the CRV Phase 1 in early December 1999, appropriately phased with NASA's RFP, and is synchronising the detailed design activities performed by ESA contractors with the overall vehicle design activities being performed by US industry during Phase 1.

17/18 November 1999: The Night of the Leonids

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The 'Leonids' are small dust particles that enter the Earth's upper atmosphere with very high velocities (about 70 km/s). They are the result of the Earth passing through the path of the debris cloud of the comet Tempel-Tuttle. The meteor activity associated with Tempel-Tuttle is called a 'Leonid event' because the meteors appear to be coming from the direction of the constellation Leo. There is evidence that this comet has created meteor showers and storms for more than 1000 years. Named after Ernst Tempel and Horace Tuttle who first discovered it in 1865 and 1866, the comet has a nucleus about 4 km in diameter and orbits the Sun with a period of just over 33 years. When at its nearest to the Sun, it also passes close to the Earth's orbit. The last perihelion passage of Tempel-Tuttle occurred on 28 February 1998. The Earth passed through that same region of space on 17/18 November 1999 and, because of the comet's recent presence, an increase in the amount of cometary debris was indeed encountered.

The 1999 Leonid meteor storm

After the Leonids had failed to live up to expectations in 1998, the night of 17 to 18 November 1999 was awaited with great suspense, not least because predictions by Asher and McNaught suggested that there would be around 1500 meteors per hour. The intensity of the Leonids is usually measured in terms of Zenithal Hourly Rate (ZHR). The ZHR is a measure of how many meteors per hour would be visible if the observed shower were to come from the zenith direction under optimum observing conditions (no Moon and no clouds). The limiting visual magnitude is set at 6.5, which is equivalent to a particle mass of about 100 µg (for objects travelling at 71 km/s) or a particle diameter of about 0.5 mm.

The Leonids certainly came on this occasion! Visual observations revealed a distinctive peak with a ZHR of more than 5000 shortly after 2 o'clock UT (Greenwich Mean Time) on 18 November. It turned out to be one of the most impressive meteor storms recorded this century. Only in 1966 was there a more intense storm, when observers reported rates of up to 150 000 meteors per hour. The originator of that storm was the same comet, Tempel-Tuttle, just one revolution earlier!

Asher and McNaught's predicted time of peak activity of 2h 08m UT was confirmed to within at most a few minutes, although the amount of activity observed was significantly higher than predicted. From modelling, it has been concluded that the main activity was caused by the three-revolution-old dust trail of comet Tempel-Tuttle, which means that the Leonids observed at around 2 o'clock on 18 November 1999 were ejected from the comet about 100 years ago.

All observers who were able to view the peak under good sky conditions reported an abundance of faint meteors and a relative absence of fireballs. Ten minutes before the time of peak activity, at 1h 53m ± 5m UT, the ZHR profile shows a secondary peak of about 3500. Asher and McNaught mentioned 1h 53m UT as the nodal crossing time for the one-revolution-old trail, but did not expect activity from it. ZHR levels were above 1000 from roughly 1h 20m to 2h 45m UT.

Observers under the ESA flag

ESA participated in several observing campaigns in order to be sure not to miss the Leonids. The main source of data was a joint USAF/NASA/CRESTech campaign, which was co-sponsored by ESA. An array of radars was operated in Alert, Canada from the evening hours of 15 November until the morning hours of 19 November. These radars, at 83 deg latitude, could see the Leo constellation 24 hours per day and were not affected by bad weather conditions. Automated TV detection in Israel, the Canary Islands, Florida, Hawaii and Kwajalein Atoll, as well as visual counts from these same locations, complemented the radar data. ZHR-values were e-mailed to ESOC initially every 60 minutes, and during the peak every 15 minutes. Figure 2 shows the reported Leonid activity for the two days around the maximum.

The second data source was an ESA contractor, Michael Schmidhuber, flying on one of the two aircraft organised by Peter Jenniskens from NASA Ames Research Center. From these two aircraft, the Leonids were recorded in stereo-mode, allowing a more accurate orbit determination. During the peak in the Leonid shower, the planes were flying from Israel to Portugal and the observer teams on board had spectacular seeing conditions well above any possible clouds. The voice reports – 'We are counting more than 2000 meteors per hour and it is still increasing', Schmidhuber told us by telephone – were complemented by the downlinking of the meteor counts at 5 minute intervals to a Web server, which was accessible from ESOC.

Last but not least, ESA sent staff to southern Spain to make video observations from the ground. One set of cameras was operated by Detlef Koschny at the Sierra Nevada Observatory, and a second set by Joe Zender on top of Calar Alto, 60 km further west. The analysis of the video images is still in progress, but Koschny, assisted by André Knoefel, provided visual meteor counts during the morning hours of 18 November. These counts, shown in Figure 3, were transmitted to ESOC by e-mail in near real time.

In addition to these three real-time observing campaigns, a more research-directed observation campaign was conducted at Wachtberg near Bonn, Germany, with a 34-m radar antenna operated by the Research Establishment for Applied Sciences, FGAN. By looking with their L-band (1.33 GHz) radar directly into the Leo constellation, it was possible to analyse the trajectory profiles of some Leonids during their disintegration in the Earth's upper atmosphere.

Prudent spacecraft operations at ESOC

What was done with the observational data from the three sources? At ESOC they were displayed in real time on a Web page. This was the only Web site via which interested parties around the World could follow the peak in Leonid activity in real time, unless they themselves were lucky enough to be under a clear night sky with the constellation of Leo above the horizon. There were not only

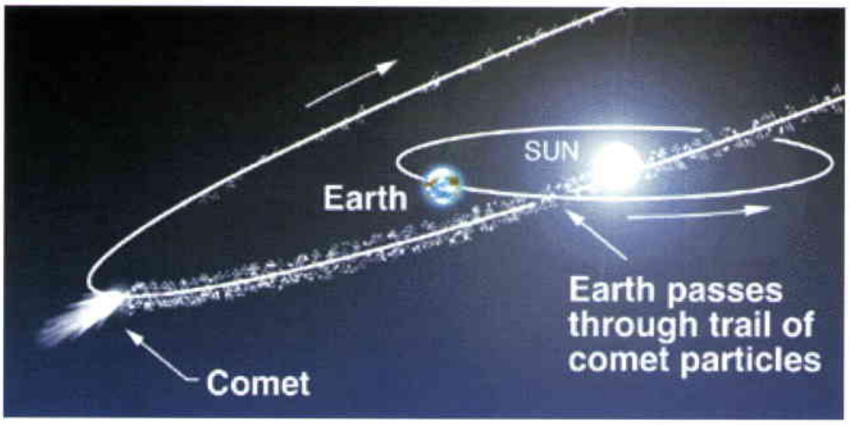
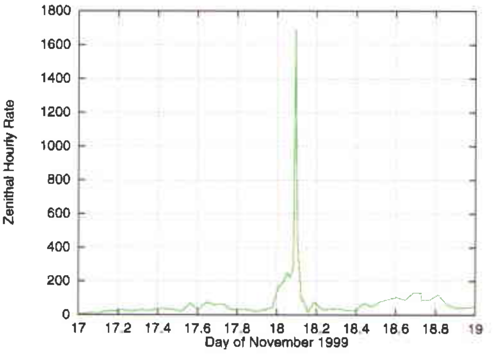


Figure 1. Comet Tempel-Tuttle's orbit crosses that of the Earth

journalists and amateur astronomers among the 15 000 hits on the Web site – it also provided the spacecraft operators at ESOC with a close eye on the levels of Leonid activity. The operators were worried about the physical integrity of the ESA spacecraft – ERS-1 and 2, Marecs B2, and ECS-4 and 5 – under their direct control, but SOHO and the Hubble Space Telescope could, it was feared, also be damaged by a hit from a tiny meteoroid.

The ERS-1 and 2 payloads were switched off in the evening hours before the predicted peak, to minimise the risk that a meteoroid impact might damage the spacecraft electronics due to plasma being generated by the collision. In addition, the thrusters and gyroscopes were warmed up, the spacecraft were switched to 'fine-pointing mode' (a more robust flight mode), the solar arrays were placed in an automatic Sun re-acquisition mode, the payload heater thresholds were lowered, and continuous checks were performed on the on-board memories and the power systems.



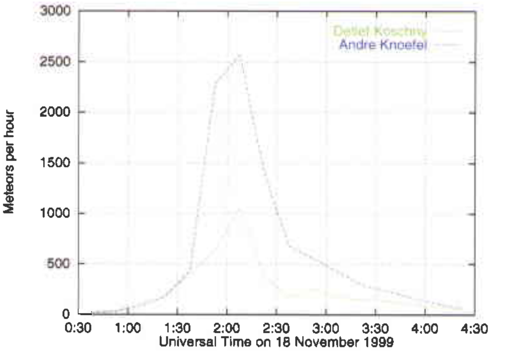


Figure 2. The Zenithal Hourly Rate (ZHR) of the Leonids as observed with an array of radars located in Alert, Canada, automated TV detection in Israel, the Canary Islands, Florida, the Hawaii and Kwajalein Atoll, as well as visual counts from these same locations

Figure 3. Counts of meteors per hour as recorded by D. Koschny (green curve) and A. Knoefel (blue curve) at the Sierra Nevada Observatory in Southern Spain. Limiting magnitude was 5.8 for Koschny and 6.4 for Knoefel: hence the difference between the two curves

At 2:48 UT, Perth had acquisition of signal from ERS-1, and half an hour later from ERS-2. All parameters were nominal, but Alan Smith, Head of Flight Operations Division at ESOC, only declared the Leonid risk as being over when the two ERS spacecraft reported nominal status during their passes over Kiruna at 7:23 and 7:54 UT, respectively. Only then was it certain that the Leonids had passed without causing any damage. Fortunately, the other spacecraft flying under the ESA flag had similarly survived the 'Night of the Leonids' unscathed.

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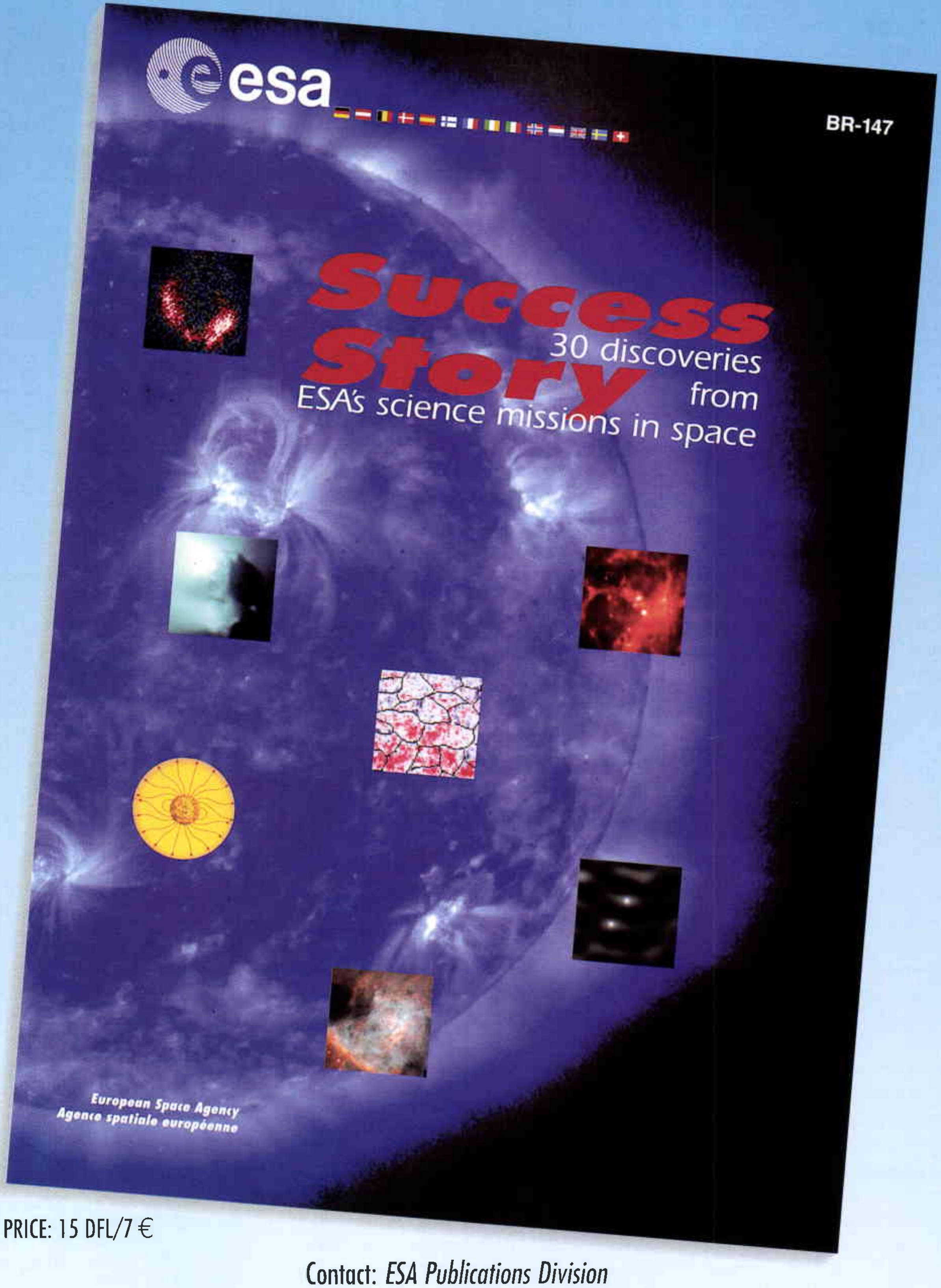

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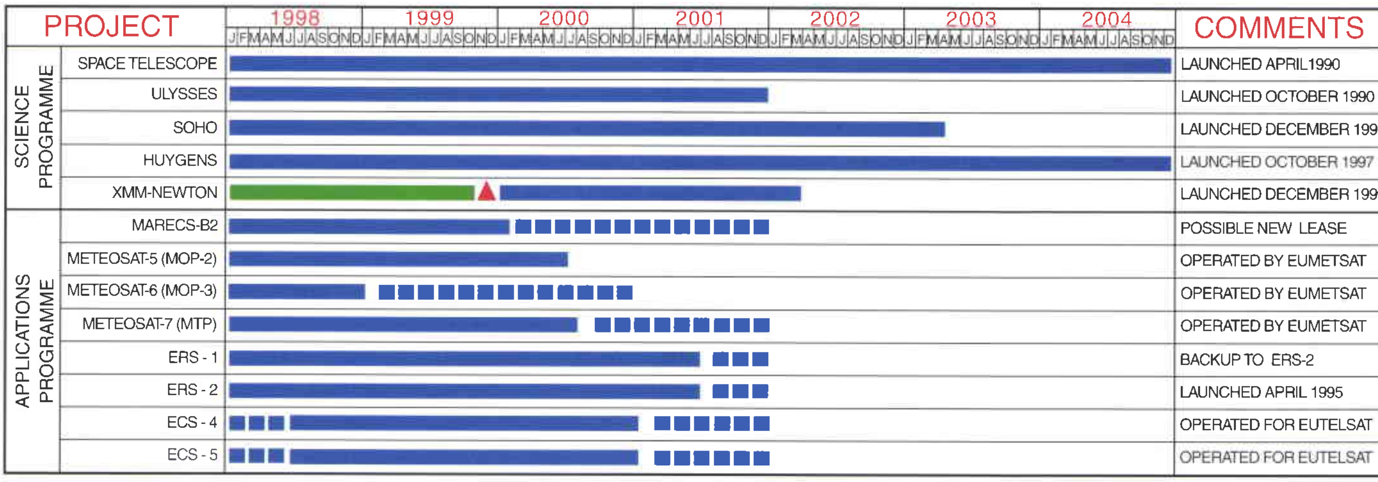

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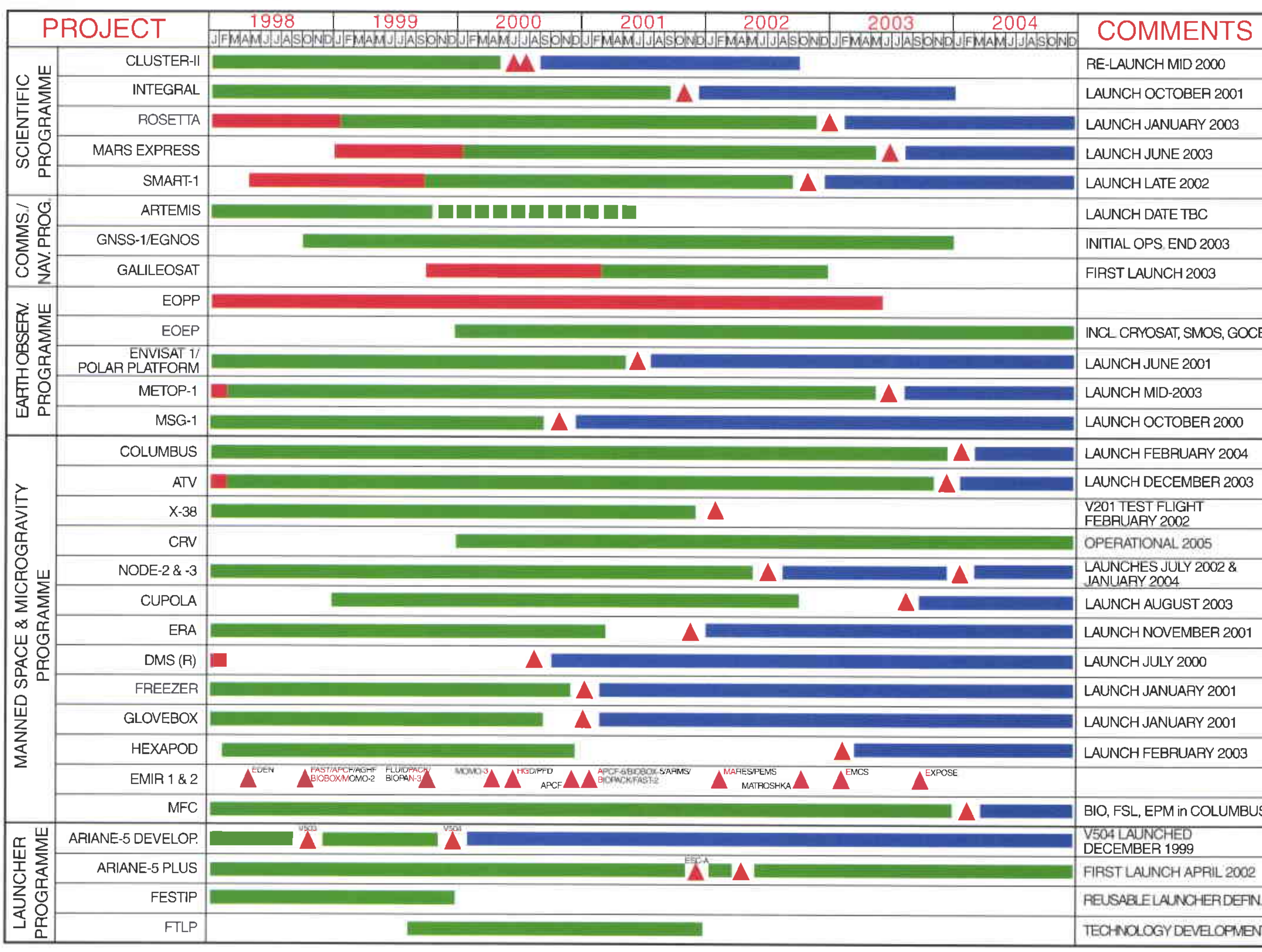

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OPERATIONS | ADDITIONAL LIFE POSSIBLE | RETRIEVAL | STORAGE

Cluster II

The Acceptance Review (AR2) for the second spacecraft (FM7) has been successfully held and all open work required to be completed before shipment to the launch site has been identified. The first two spacecraft (FM6 and FM7) are back at Dornier in Fredrichshafen (D) awaiting final refurbishment and packing for shipment to the launch site. The third spacecraft (FM8) and last spacecraft (FM5), which was originally called 'Phoenix', have both successfully completed all functional testing and are at present in IABG in Munich (D) undergoing their environmental test programme. All testing and refurbishment on all four spacecraft is planned to be completed by mid-March and shipment to Baikonur is planned with two flights in early April.

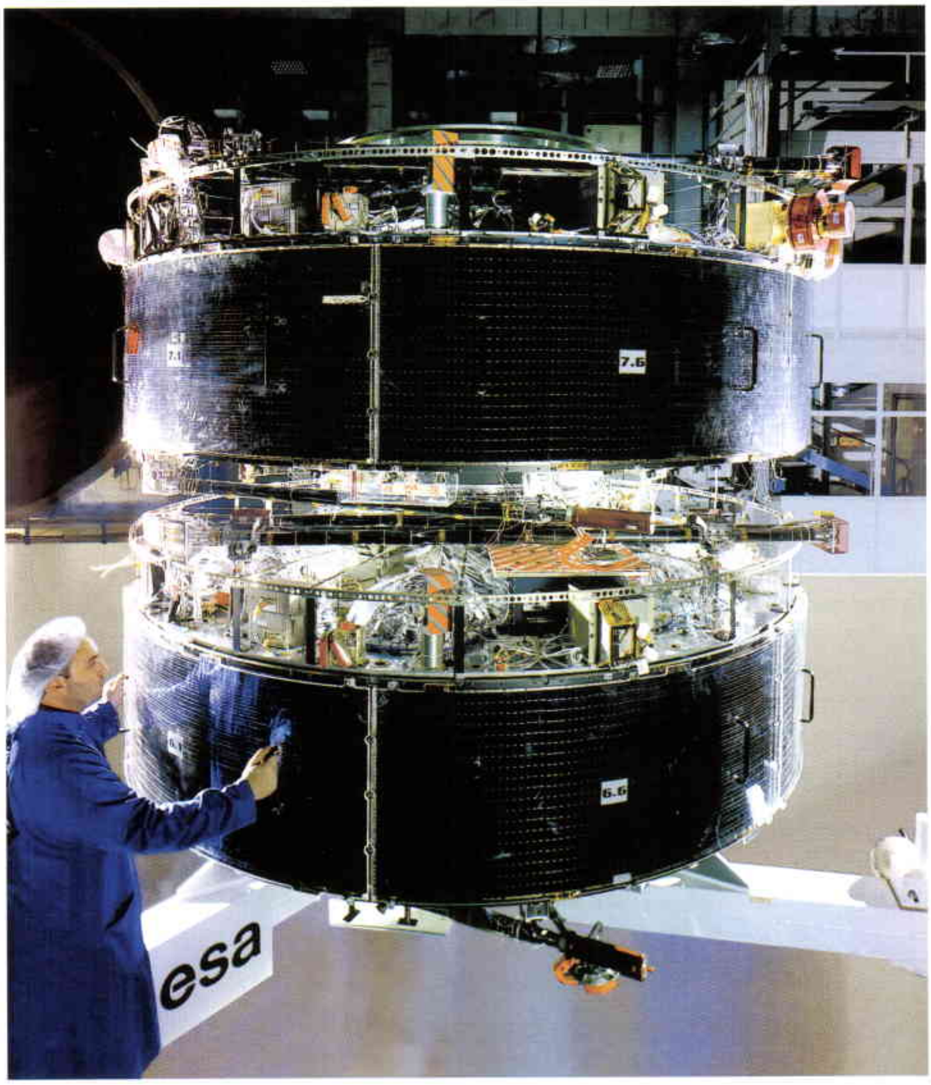
A public-relations event was held at IABG on 24 November, when all four fully integrated spacecraft were together in one room – the only time that this will happen in Europe.

Turning to the ground segment, the front-end of the 15 m dish, moved from the Odenwald ground station in Germany, has successfully undergone acceptance testing at its new site in Villafranca in Spain. System-validation tests have been performed on all four spacecraft, commanding each one directly from ESOC in Darmstadt (D). The operations procedures are now ready, and the operations team build-up is also complete. Flight simulations will start in February and will continue until the launches.

The Science Data System is also now ready and end-to-end system functional testing, from the Principal Investigators sending commands to their instruments to the Data Centres receiving their data, are in progress.

The ground testing of the new Fregat upper stage for the Soyuz launch vehicle was successfully reviewed at a Launcher Design Review and the first Fregat qualification flight model (and Soyuz) has been shipped to the Baikonur Cosmodrome in Kazakhstan. The first flight is scheduled to take place before the end of January.

All elements of the Cluster-II mission are still on schedule for the launching of the four spacecraft by two launches in June and July 2000.



Two of the four Cluster-II spacecraft, at IABG in Munich (D)

ISO

Version 3 of the ISO Data Archive, located at <www.iso.vilspa.esa.es>, was released in December 1999 for use by the worldwide astronomical community. This marked a major upgrade from the user point of view. Links are now provided from the observations in the archive to the refereed papers in which they were published. New tools are available to manipulate the 'quick-look' data products so as to get a better idea of the scientific content of an observation prior to deciding to retrieve it.

A second theme of this release was closer integration with other astronomical archives. From within the ISO archive's user interface, access to data from the IRAS infrared all-sky survey corresponding to specific ISO observations is now only a few clicks away. The IRAS data itself is served from the Infrared Processing and Analysis Center in California, where a mirror of the ISO archive's front-end has been set up. A new mechanism is now in place to enable other archives to serve ISO data through their user interfaces.

Integral

By October 1999, the arrangement with the Russian Aviation and Space Agency (RAKA) and the launcher adaptation industrial contract were both fully approved and running. This marked a major milestone for the programme because it secured the Proton launch scenario and removed a long-running uncertainty for the mission.

A Critical Design Review was held in December 1999. This review, which covered all mission elements, drew the following conclusions:

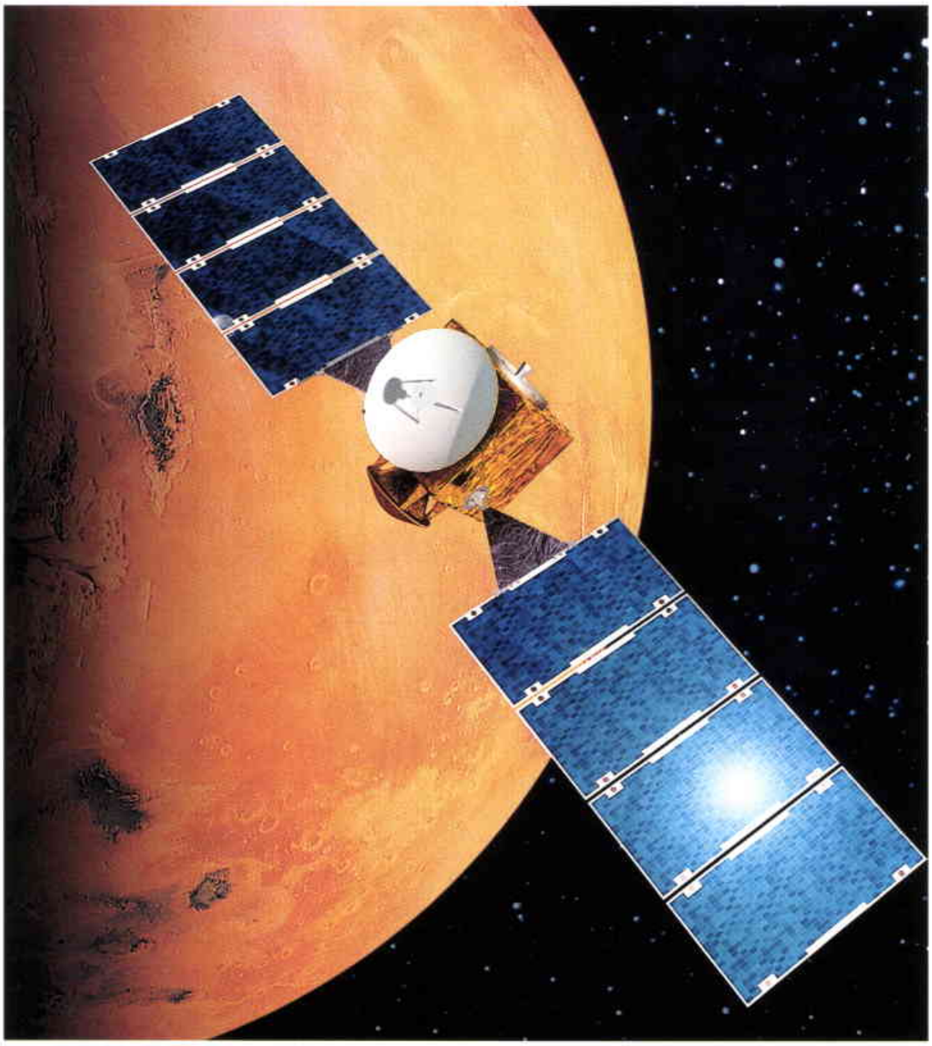
- The spacecraft has completed its Structural and Thermal Model (STM) and its Engineering Model (EM) programmes successfully and is now progressing nominally. No major technical issues have been found and the proposed Flight Model (FM) programme is adequate for an October 2001 launch.
- The planning for the payload instruments could not, however, support such a launch date. In view of the potential crisis, payload teams were given until the end of March 2000 to provide committing plans.
- The problem of overall coordination of the three ground-segment elements was also noted as a concern.

As a result of the Review, the spacecraft, the launcher and the mission-operations activities are to continue as planned for an October 2001 launch up to the point where the payload is needed. The status of the payload will be reviewed again in March 2000.

Integral hardware in the Alenia clean room in Turin (I) (from left to right): FM Payload Module structure, FM Service Module, EM spacecraft

Mars Express

The main event in late 1999 was the Preliminary Design Review (PDR). This review constituted the end of the design phase and, if closed out successfully, would lead to the formal starting of the spacecraft development programme. The review cycle included all elements of the payloads, the ground segment and the spacecraft. To this end, individual instrument reviews and a Ground Segment Requirements Review were held. Their results were made available to the Science and Engineering Review Team, a group of 14 ESA engineers and one independent scientist. The main task of this team was to review in detail the design and all of the specifications made available by the spacecraft Prime Contractor, Matra Marconi Space, Toulouse (F). After a short preparation period at ESTEC, the team attended a one-week-long co-location exercise in Toulouse to work face-to-face with the industrial team. A detailed report was drawn up addressing all aspects of the mission implementation. The Review



Artist's impression of the Mars Express spacecraft

Board will hold its final meeting in mid-January 2000.

A very similar review process was also applied to Beagle-2, the Lander on Mars Express. The ESTEC experts concluded that the lander design is sufficiently mature and ESA's Science Programme Committee (SPC) was advised to finally confirm Beagle-2 for inclusion in the spacecraft programme.

A Science Working Team meeting was held in late September, with the main focus on the definition of the in-flight instrument operations during various phases of the mission.

SMART-1

SMART-1 is the first of the 'Small Missions for Advanced Research in Technology' within the ESA Horizons 2000 Scientific Programme. This first mission is dedicated to the testing of new technologies for the future 'Cornerstone' missions, using Solar Electric Propulsion (SEP) in Deep Space. The chosen planetary target for the mission is the Moon, and the target orbit will be polar, with its pericentre close to the lunar South Pole. The pericentre altitude lies between 300 km and 2000 km, while the apocentre will extend out to about 10000 km. The planned spacecraft thrusting profile provides for extended periods of 'cruise science' during the cruise phase of the mission on the way to the Moon.

The SMART-1 spacecraft will be launched late in 2002 by an Ariane-5, as an auxiliary passenger, into a Geostationary Transfer Orbit (GTO). The expected launch mass is about 350 kg, including 15 kg of payload. The SEP selected is a Hall-effect thruster known as PPS-1350, which will be used to spiral the spacecraft out of GTO and to perform the lunar capture and final orbit insertion operations. The trajectory has been optimised by inserting coasting arcs, and the Moon's gravitational field will be exploited for multiple weak gravity assists.

The SMART-1 mission started as a feasibility study (Phase-A) in May 1997. A Phase-B followed once the necessary funding had been secured, in April 1998. The closure of the Phase-B was sealed by the successful completion of the System Design Review in June 1999. A bridging phase was agreed to cover the on-going activities until formal approval for the mission by the Agency's Science Programme Committee (SPC) was granted. At its meeting in September 1999, the SPC approved the mission, and in November 1999 the scientific payload was also formally confirmed.

The Main Development Phase (Phase-C/D) began in October 1999 and is expected to be concluded with a Flight Acceptance Review in the second half of 2002. The industrial consortium is led by Swedish Space Corporation (SSC). The Phase-C/D contract with SSC was signed in November, as was the contract with Arianespace for the SMART-1 launch.

Artemis

The satellite's system-level testing is now complete and it is ready for shipment to Tanegashima in Japan for launch. Unfortunately, the launch prior to that of Artemis suffered a failure and NASDA are therefore carrying out a detailed inquiry to establish the cause and to identify any necessary modifications to the vehicle. Consequently, the launch schedule for Artemis can only be reestablished once these activities have been completed. In the meantime, the satellite has been placed in storage at ESTEC.

EOEP

Strategy and future programmes

Ahead of initiation of the Earth Observation Envelope Programme (EOEP) in January 2000, the Executive, together with the Earth Observation Programme Board (PB-EO), has now established clear working methods and initial priorities.

In addition to the first Earth Explorer Opportunity Missions, selected in June, at the November PB-EO the first Earth Explorer Core Missions were selected. This followed the Granada II meeting, at which the four candidate Core Missions were presented to and discussed by the European Earth Science community and then subjected to detailed peer review and Earth Science Advisory Committee (ESAC) recommendation. Based on this recommendation, the PB-EO has selected the Gravity Field and Steady-State Ocean circulation Mission (GOCE) and the Atmospheric Dynamics Mission (ADM) as the first two missions. Detailed descriptions of these missions are to be found in ESA SP-1233 (Vols. 1 and 4), available from ESA Publications Division.

Future missions

Following the completion of the first Earth Explorer Core Mission selection cycle, the Executive is now initiating the second-cycle Call for Mission Proposals. It is intended to seek the widest possible international collaboration in the process.

The next new development in Earth Observation is expected to be the elaboration of an Earth Watch Programme. Such a programme is essential if Europe is to put into place a system for long-term monitoring of the Earth's environment.

ERS

The mission

The ERS mission has continued into its ninth year, granting long-term observations and providing scientific data with very high quality and continuity.

The ERS system operations have continued very smoothly, with excellent performances from the satellites and the ground segment. The mission was ensured by ERS-2, whilst the ERS-1 payload was in hibernation.

The technical status and performance evolution of the satellites permits one to envisage full-mission continuity until Envisat becomes operational, and permanence of the wind data until the Metop-1 launch.

Satellite operations

The implementation of new Instrument maintenance activities has improved the satellite's performance, increasing data availability to more than 90%.

Special measures were taken to protect the most sensitive elements of the two satellites from the Leonids meteorite storm. Despite the storm's high intensity, no anomalies were detected during or after its passage.

ERS-1/2 SAR interferometry is continuing, with the acquisition of one or two pairs of images each day.

A new attitude and orbit control strategy has been developed to be able to maintain satellite pointing performance using a single gyro instead of three. This will allow the operational lifetime of the gyro system to be extended

The entire ERS system was upgraded and tested for the year 2000 transition. An overall end-to-end test certified the system as Y2K-compliant and no problems have been detected around 1 January.

Artist's impression of the Metop satellite

Metop

The major achievement during this period has been the final step in the establishment of the legal basis for the Metop-1 Programme, with the signature of the ESA/Eumetsat Cooperation Agreement on 7 December 1999. This allowed, and was immediately followed by, the signature of the Metop Industrial Contract, by the Director General of ESA Mr A. Rodotà, the Director of Eumetsat, Dr. T. Mohr, and the Chief Executive Officer of Matra Marconi Space, Mr A. Carlier. The signature of these two documents followed a period of intense activity by all of the project teams involved in finalising the last details of the contractual and technical baseline, including resolution of all Requests for Waivers and integration of accumulated Contract Change Notices.

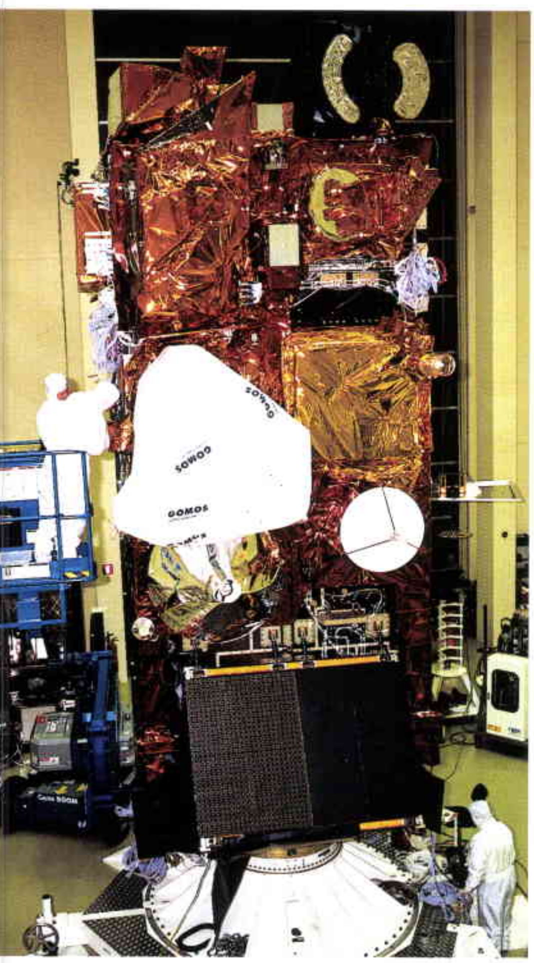
A parallel activity to finalise the GOME-2 Contract is now also complete, and its signature is anticipated in early 2000.

In the meantime, the development work on the satellite has continued. The first of the Customer Furnished Instruments have been delivered for Payload Module engineering-model integration at DaimlerChrysler Aerospace (Dornier): the AMSU, AVHRR and HIRS and, recently, the SEM, provided by NOAA/NASA. They are currently undergoing initial integration with the NOAA Interface Unit, a dedicated unit within Metop, which emulates the command, control and measurement data interface of the NOAA Tiros spacecraft.

Envisat/Polar Platform

Envisat system

The system activities have focused on two key areas: optimisation of the remaining verification activities on the satellite and overall ground segment before launch, and the preparations for the in-orbit commissioning, in particular the setting up of the payload calibration/validation teams.



The Envisat spacecraft during its testing at ESTEC (NL)

Satellite activities

Following completion of the Payload Module (PLM) Thermal Balance/Thermal Vacuum (TB/TV) test in the Large Space Simulator (LSS) at ESTEC (NL) in August 1999 and post-test alignment measurements, a number of instruments/units were removed and returned to their suppliers for refurbishment or completion of acceptance. Some of these have already been returned and re-integrated (RA-2). In addition, the flight-model MERIS instrument and MIPAS Optics Module have been delivered and successfully integrated.

A problem observed during the PLM TB/TV test resulting from insufficient venting of some parts of the PLM (in particular for the X-band subsystem) has been cured. The flight-model Service Module was prepared for a shock test to be executed with Ariane-5 representative elements (shock generator and clamp-band separation system).

Next year should see the finalisation of the flight configuration, with the integration of the remaining instruments (Sciamachy and ASAR), followed by functional and environmental testing.

Following a detailed reassessment and scrutiny of the schedule for satellite activities up to launch, taking into account the latest schedule of deliveries, the target Envisat launch date has been revised to end-June 2001.

Envisat payload
The MIPAS and MERIS flight-model instruments have been delivered and integrated on board the satellite. The integration tests of the complete ASAR flight-model instrument are well advanced and the ASAR delivery for integration on the satellite is expected early in 2000. With delivery of the SCIAMACHY flight-model instrument also planned for early 2000, the complete payload complement will then be integrated onto the satellite.

Envisat ground segment
The development and integration of the Flight Operations Segment (FOS) is proceeding according to plan. Preparations for the next compatibility test with the satellite are in progress. The deployment of Payload Data Segment (PDS) Version 2 has been completed at the two ground-station sites of Kiruna,/Salmijarvi (S) and ESRIN, Frascati (I). The corresponding acceptance testing is in progress. Compatibility tests between FOS and PDS mission planning facilities have already been initiated. The PDS version V3 activities have been initiated.

The Processing and Archiving Centre (PAC) implementation activities are in progress with most of the assigned PACs.

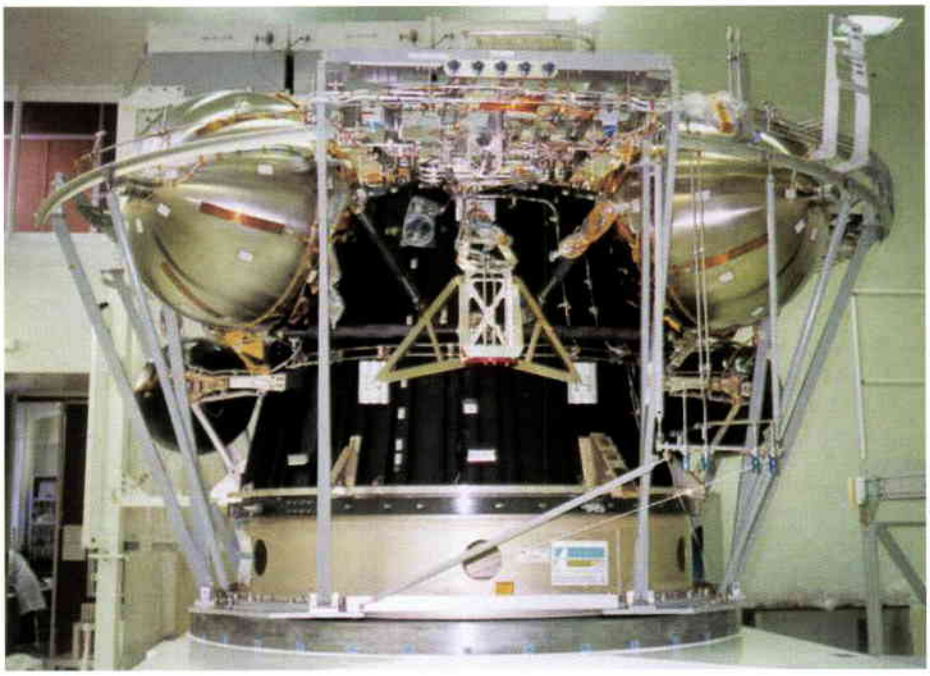
The Invitation to Tender (ITT) for the commercial distributors was released last autumn and the offers received at the end of the year are currently being evaluated.

Meteosat Second Generation

The engineering-model satellite is currently undergoing final testing, with end-to-end spin tests to followed by a radiated electromagnetic-compatibility retest.

The MSG-1 flight-model satellite is now fully integrated and, after initial reference testing, is being prepared for mechanical environmental testing. The accompanying picture shows the flight-model propulsion subsystem on its transportation and integration jig.

The predicted launch date for the MSG-1 spacecraft remains October 2000. MSG-2 and MSG-3 also remain on schedule, with a predicted launch date for MSG-2 in 2002, and an anticipated storage date for MSG-3 in 2003.



The MSG flight-model propulsion subsystem on its transportation and integration jig

Investigations into how to overcome the Ariane-5 shock problem are in progress. Representative Ariane-5 flight data from two other satellites on a SYLDA-5 frame are expected to be available in early 2000.

International Space Station

European participation in the ISS Exploitation Programme
From the commercial utilisation workshop that was held in October at ESTEC, and mid-term reviews in December of the on-going studies on strategic marketing of the ISS, a clearer picture of the ISS's commercial market potential is emerging. ESA's approach to the commercialisation of utilisation, based on the outcome of these and associated activities, will be presented by the Executive in February 2000.

ISS Overall Assembly Sequence
Following the second of two Proton launch failures (in July and October 1999), all Proton launches were put on hold pending the outcome of a State Commission investigation. Consequently, the previously planned launch window for the ISS Service Module of 26 December to 16 January was no longer valid. Current indications are that the launch is unlikely to take place before mid-2000. Once the Service Module has been launched, the Assembly Sequence will be reviewed and updated.

Columbus laboratory
Critical Design Reviews (CDRs) at levels below that of the overall system are about 90% complete, with no major problems having been identified. Detailed planning for the system CDR is at an advanced stage. Qualification-model manufacture is underway and some qualification testing has already been completed. The first data-management interface tests between Columbus and the ISS have also been conducted successfully. Flight software coding is at an advanced stage and integrated test cases will begin early in 2000. Primary-structure assembly welding has been completed (see accompanying photograph) and integration of the secondary structure has begun. The development of major ground test facilities – the Flight Trainers and the Rack Level Test Facility – is underway.

Columbus Launch Barter
Nodes-2 and -3
The Structural Test Article welding is nearing completion. The Node-2 design is progressing well and some flight hardware items (harnesses and thermal-control elements) have been released for manufacture. The Node-3 design effort has been re-initiated following the Reference Configuration Review in mid-1999, and the package of associated design changes is under review and negotiation.

Cryogenic Freezer Racks
A new technical and programmatic specification issued by NASA is being reviewed.

Cupola
The Cupola project has been realigned following the decision by NASA to delete the second flight-model Cupola for financial reasons. The resulting design and operational changes and their associated programmatic influences have been established and negotiated with industry, and the effects on the ESA/NASA barter have been identified. The forging for the upper part of the Cupola Structural Test Article was broken during cold stretching. This failure was due to tooling design problems, and a second unit was successfully manufactured after the appropriate tooling changes had been implemented. Preparations are underway for the Design Consolidation Review in the first quarter of 2000.

Automated Transfer Vehicle (ATV)
The ATV System Preliminary Design Review (PDR) is planned for March/April 2000, pending a successful conclusion to the Avionics PDR scheduled for January. Technical and programmatic agreements have been reached between ESA, AM-L/Alenia and RSC-Energia on the Russian hardware procurement. Alenia and RSC-Energia should conclude their negotiations early in 2000.

The Requirements Review for the software that RSC-Energia will develop to support the re-boost function was successfully concluded in November.

X-38/CRV and Applied Re-entry Technology (ART)
X-38/ART activities have continued as planned, without significant difficulties being encountered. During October, the X-38 aerodynamic and aerothermal databases were delivered to NASA, and acceptance testing of the V201 flight rudders was successfully completed.

With the participation of France and Spain in the CRV programme slice approved, the subscriptions for CRV activities now total 57.72 MEuro. In addition, a letter of intent from Italy regarding a participation of approximately 30 MEuro was received in November, and its formal subscription is expected in early 2000. CRV Early Phase 1 design activities have been kicked-off and the corresponding budget was approved by the Manned Space Programme Board (PB-MS) in November.

Atmospheric Re-entry Demonstrator (ARD)
Flight data exploitation is progressing well and the second Progress Meeting was held on 26 November.

Ground-segment development and operations preparation
The Columbus Control Centre Phase-B2 activities have been extended to allow time for more detailed definition of the system architecture. The Phase-C/D kick-off is now planned for the first quarter of 2001. The ATV Control Centre system-definition activities are continuing according to plan.

The Columbus Functional Crew Trainer Phase-C/D has been initiated and is proceeding satisfactorily, with first major Design Review scheduled for February 2000. The ATV Trainer Phase-A study has been completed and the Request for Quotation (RFQ) for the System Requirement Definition Phase will be issued shortly.

Utilisation
Promotion
Funding for 24 Microgravity Application Programme (MAP) projects was approved in December, with ESA paying approximately 35% and the participating institutes, national agencies, third parties and industry providing the remainder. The level of the industrial contribution – more than 25% of the total value of the projects – is a clear sign of the potential interest on the part of European industry in utilising the ISS for research purposes.

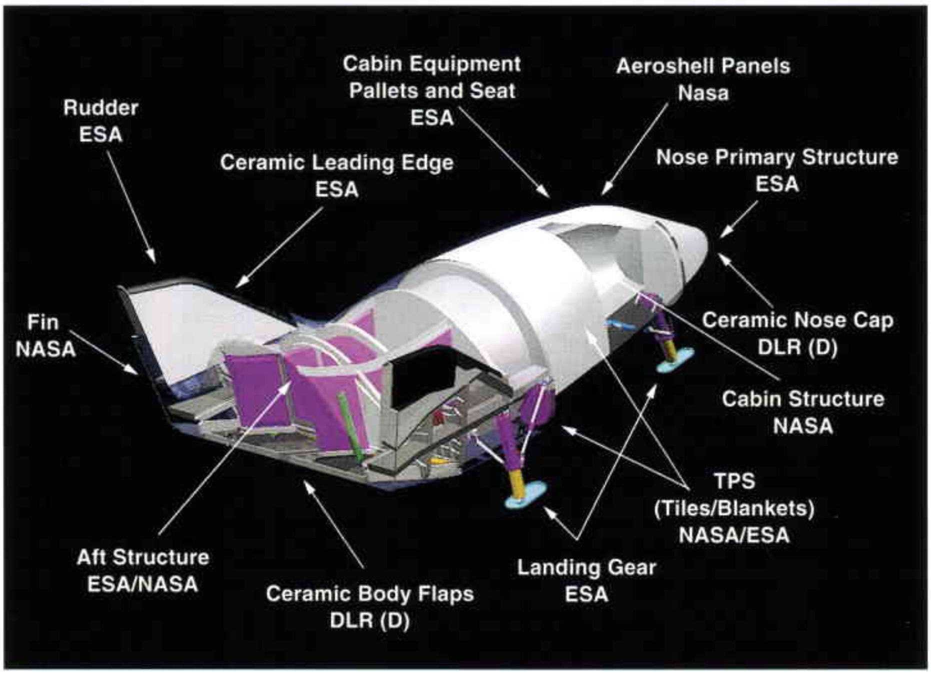
Preparation
The first meetings of the Programme Committee for the Global Forum 2000 on Space Station Utilisation and of the Multilateral Co-ordination Working Group on Commercialisation Programmes for ISS were held in early November in Washington DC. The Space Station User Panel (SSUP) met in mid-November.

Hardware development
There were continuing problems between the Brazilian Space Agency and NASA regarding the schedule for the development of the Express Pallet Adapters for external ISS payloads, including the ESA payloads, and negotiations continued with industry on the price for the integration of ESA payloads on the Express Pallet Adapters.

The PHARAO atomic clock, which is at the heart of the joint ESA/CNES ACES (Atomic Clock Ensemble in Space) project, will not be ready until 2003, leading to a launch in early 2005, and hence a 1.5 year delay in the ACES mission.

Astronaut activities
With the arrival of astronauts M. Tognini (F) and C. André-Deshays (F) and astronaut candidate F. De Winne (B), the single

Cut-away view of the X-38/CRV lifting-body vehicle



European Astronaut Corps is now at a nominal strength of 16 members.

The much-publicised Hubble Servicing Mission STS-103 took place in December 1999 with two ESA astronauts, J.-F. Clervoy and C. Nicollier, on board. Discussions with NASA on the involvement of an ESA astronaut in the STS-107 mission and participation by ESA astronauts in the Mission Specialist 2000 class are in progress, as well as an exchange of information on flight opportunities with the Russians.

Early deliveries

Data Management System for the Russian Service Module (DMS-R)

The RSA and RSC-Energia managements have agreed that the corrective action taken to eliminate a DMS-R problem ('boot problem') has been successful and there is no longer any reason to consider this a condition for clearing the Service Module for launch. The software 'patch' that was provided was subsequently integrated into the DMS-R flight software, and successfully verified on the engineering model of the Service Module in Moscow and the flight unit at Baikonur. All Service Module avionics testing involving DMS-R was successfully completed at Baikonur during November.

European Robotic Arm (ERA)

The Critical Design Review (CDR) was successfully completed in early October and assembly of the ERA flight model has commenced and should be completed during the first quarter of 2000. The upgrading of the Mission Preparation and Training Equipment (MPTE) was completed during September, and agreement has been reached to locate one set of MPTE at ESTEC (NL), with installation planned for the first quarter of 2000. The engineering qualification model successfully completed its thermal-balance testing in the Large Solar Simulator (LSS) facility at ESTEC during October.

Laboratory Support Equipment (LSE)

The MELFI (Minus 80°C Laboratory Freezer) ground model was delivered to NASA in November and the training and engineering units are currently being integrated.

The MSG (Materials Science Glovebox) ground unit acceptance was performed at NASA in November, and the design review for the video assembly commenced in December. Integration of both the training and engineering units is in progress.

Following the decision in November to modify the re-entry configuration, a dedicated Hexapod safety review is now scheduled for February 2000.

Microgravity

EMIR-1, EMIR-2 and EMIR-2 Extension

Following the approval of an EMIR-2 Extension programme by the ESA Council meeting at Ministerial Level in Brussels last May, the contents of the programme were agreed at the Microgravity Programme Board in December.

The programme covers the provision of flight opportunities, preparatory activities for ISS utilisation and general support activities. It will continue the research in life sciences and physical sciences, with an increasing emphasis on industrial applications in the materials-science and biotechnology areas and on applications and societal benefits in the medical and biological fields.

Development activities in preparation for the STS-107 Spacehab flight for early 2001 have continued. The ESA facilities to be flown on this mission are: the Biobox, the Facility for Adsorption and Surface Tension (FAST), and the Advanced Respiratory Monitoring System (ARMS).

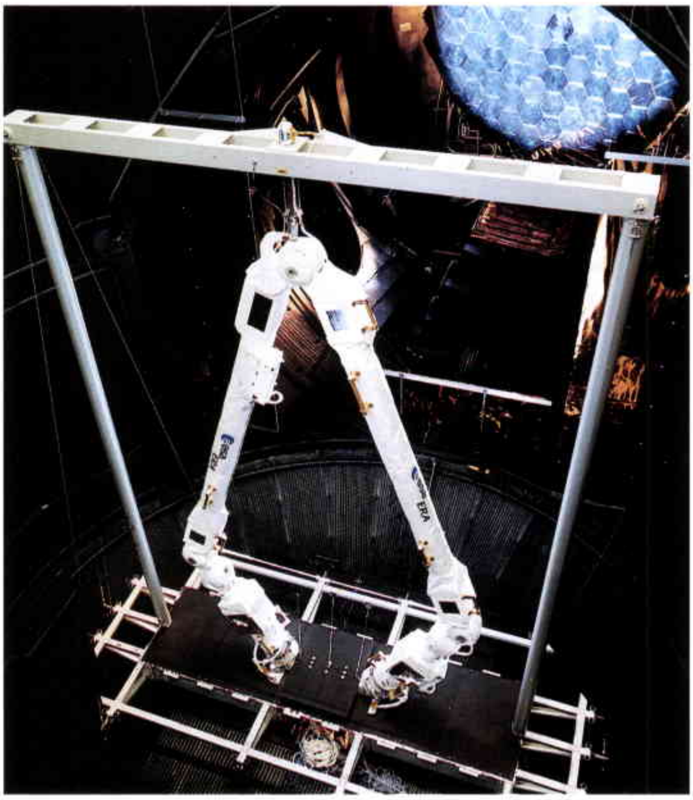
The EMIR-2 programme has also supported the development of the European Modular Cultivation System (EMCS) and the EXPOSE exobiology facility, designed to make use of early Space Station flight opportunities.

Microgravity Facilities for Columbus (MFC)

The engineering models of the Biolab, Fluid Science Laboratory (FSL) and Materials Science Laboratory (MSL) for the US Lab were well advanced and the Phase-B/C/D for the Experiment Preparation Unit (EPU) for Biolab was started.

An ESA/NASA Letter Agreement on the European Physiology Module (EPM) and Human Research Facility co-operation was concluded on 22 December. The mid-term presentation of the EPM Phase-B has taken place, and breadboarding activities for some modules have been initiated.

The Phase-B/C/D contract for the development of the EPM contribution to the NASA Pulmonary Function System has been awarded. This equipment is planned for launch in 2002, aboard the NASA Human Research Facility (HRF-2). esa



The European Robotic Arm (ERA) in the LSS for solar simulation testing at ESTEC, Noordwijk

In Brief

Portugal to be 15th ESA Member State

At ESA Headquarters in Paris on 15 December, Mr José Mariano Gago, Portugal's Minister of Science and Technology, and Mr Antonio Rodotà, ESA's Director General, signed an Agreement marking Portugal's accession to the ESA Convention. Under this Agreement, signed in the presence of ESA Council Delegates, Portugal will become the fifteenth full Member State of the Agency by 1 July 2000 at the latest.

Mr Gago had submitted Portugal's formal request to become a full Member State to ESA's Director General in October 1998. On 24 June 1999, the ESA Council unanimously approved the principle of Portugal's accession, and on 14 December it approved the terms of the Agreement.

Portugal is already involved in ESA's optional programmes in the field of satellite navigation, through a bilateral cooperation agreement signed in 1996. It has also expressed interest in contributing to activities in the fields of space science, technology and applications, including remote sensing and telecommunications. A cooperative programme was set up in 1998 to host young Portuguese engineers at ESA Establishments for training purposes.

"We warmly welcome Portugal to the European Space Agency," said ESA's Director General Antonio Rodotà, *"Portugal, which is already an integral part of the European scenario, will now, as we enter the new millennium, be able to share the benefits of cooperation in space activities"*.

A Press Conference followed the signature ceremony at ESA Headquarters.

Mr José Mariano Gago (left) and Mr Antonio Rodotà

ESA and the European Commission Sign Contracts for Galileo

On 7 December in Paris, ESA signed the contract for the GalileoSat study, the Agency's contribution to the definition phase for the Galileo satellite navigation programme. In the same week in Brussels, the European Commission gave its green light to four major contracts with industry. Together, these contracts cover the definition phase of the Galileo programme, from November 1999 to December 2000, agreed last June by the European Union Council of Ministers of Transport.

The signature of these contracts marks a true milestone in the development of a novel programme for Europe. When fully implemented, Galileo will be a multimodal global navigation satellite system that will not only give Europe independence in the field of traffic management and telematics infrastructure, but will also bring vast economic benefits for European equipment manufacturers and service industries, and create many additional jobs. Current projections envisage that the Galileo system will consist of at least 21 satellites (in medium earth orbit at 24 000 km altitude, possibly complemented by geostationary satellites at 36 000 km altitude) and the associated ground infrastructure. It will be compatible and interoperable with the planned second-generation global positioning systems.

The cost of the overall project is estimated at some 2.7 billion Euros, from which an initial amount of 80 million Euros, shared equally between the European Commission and ESA, has been allocated by European Ministers for the on-going definition phase. Financial schemes for the subsequent phases are being worked out and will be submitted to the EC and ESA Councils. Under current plans, Galileo will start operations in 2005 and achieve full operational status in 2008. esa

Mr Antonino Simeone (left), Executive Vice President for Programmes and Sales at Alenia Aerospazio, and Mr Claudio Mastracci, ESA Director of Applications Programmes, at the signing of the GalileoSat study contract

European Astronaut Centre Gears Up for New Era

In preparation for its new role in training astronauts for the International Space Station (ISS), ESA's European Astronaut Centre in Cologne (D) has strengthened its management, with the appointment of two astronauts to key positions. Ernst Messerschmid, who flew as a German astronaut on the Shuttle/Spacelab D-1 mission in 1985, has been appointed Head of EAC, taking up duty on 1 January 2000. Jean-Pierre Haigneré, who returned on 28 August from a record-breaking 188-day mission as an ESA astronaut aboard the Russian Mir space station, took up his new position of Head of ESA's Astronaut Division on 1 November 1999.

Since his Spacelab flight, Messerschmid has been a Professor and Director of the Institute for Space Science at Stuttgart University. During his time in Stuttgart, he also held the positions of Dean of the Aerospace Engineering Faculty and University Vice-President.

With ESA astronauts often working far apart at different locations, Haigneré will use his expertise in long-duration spaceflight and his long-standing international contacts to pull the team together and oversee training for future work aboard the ISS. Several ESA astronauts are in training at NASA, some are providing specialist support to development projects at ESTEC (NL), while others are following training regimes in Russia.

In addition to the above management changes, two experienced French astronauts have recently joined the European Astronaut Corps, and a Belgian trainee astronaut is set to join in January 2000. The two French astronauts, Claudie André-Deshays and Michel Tognini, joined the Corps on 1 November. Ms André-Deshays has already started work at EAC, combining her astronaut experience with a professional medical background to specialise in crew-related medicine. Tognini, resident at NASA's Johnson Space Center, is providing specialist support for the European robot arm to be launched in two years' time. Belgian Frank De Winne will join the Corps to start his training in January 2000. esa

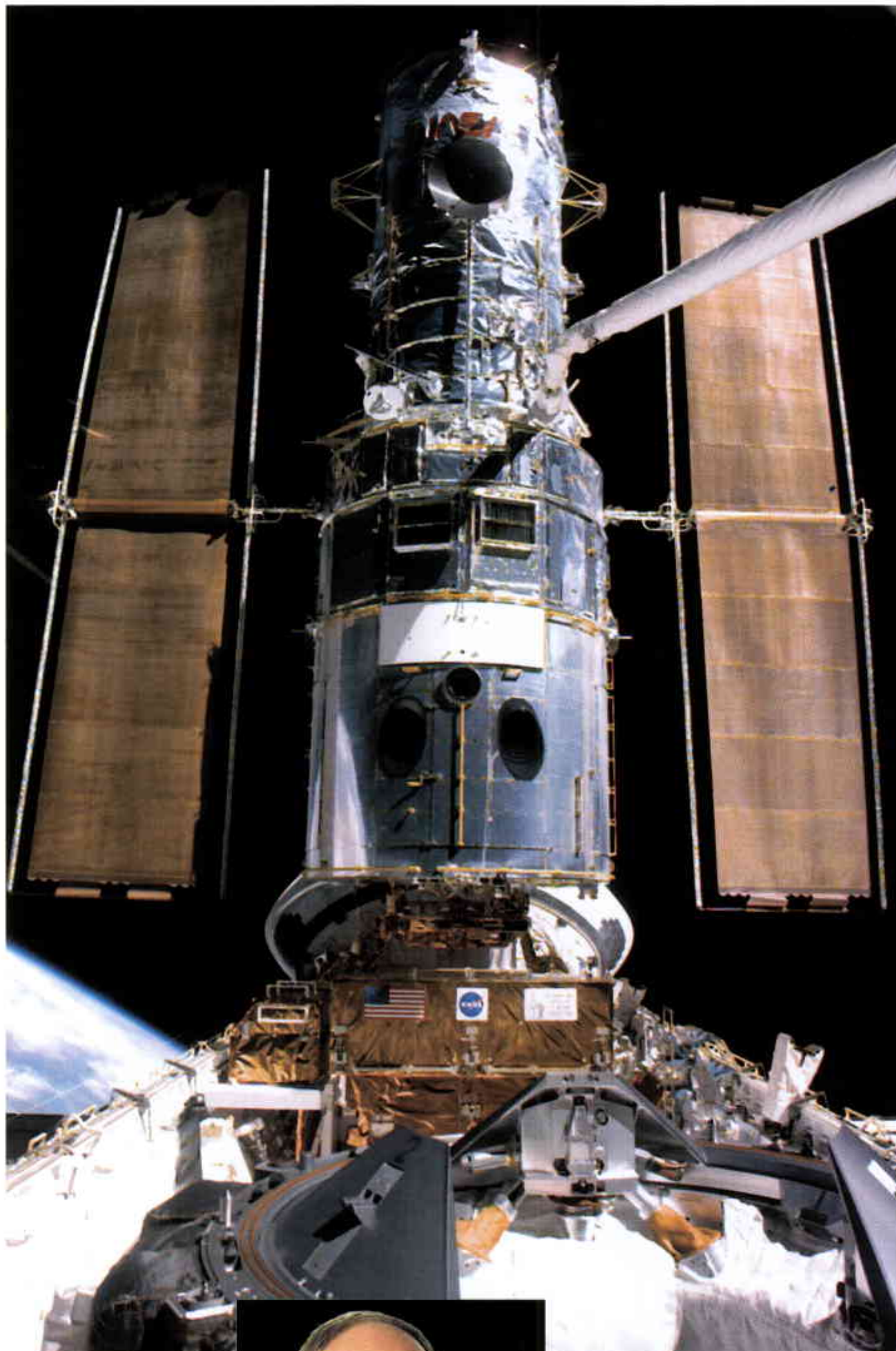
ESA Duo Back from Successful HST Servicing Mission

ESA astronauts Claude Nicollier and Jean-François Clervoy and their five fellow crew members on the Space Shuttle 'Discovery' returned safely to Earth on 28 December after a spectacular mission to service the Hubble Space Telescope (HST).

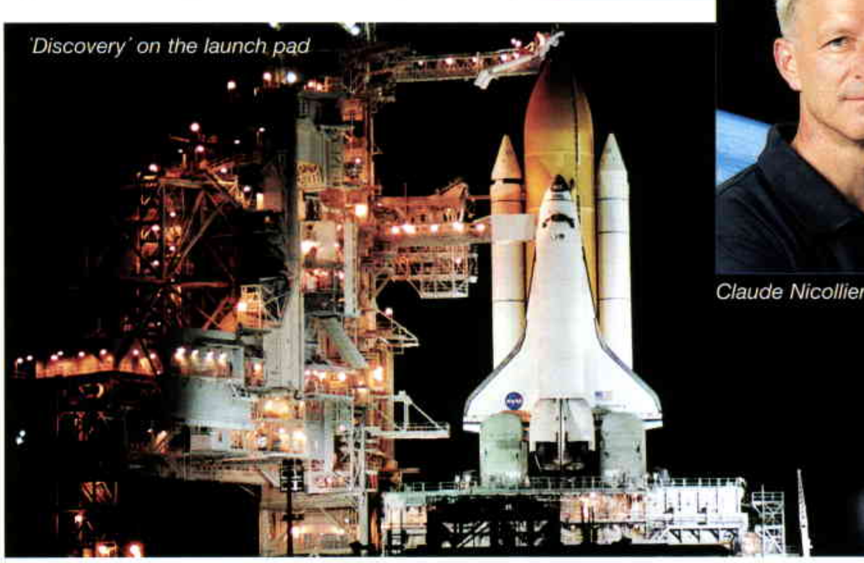
During the flight, Nicollier became the first European astronaut to walk in space from the Shuttle as he worked with US astronaut Michael Foale on a six-hour stint. On the second of three EVA days, Nicollier and Foale successfully replaced the Telescope's computer, dramatically increasing Hubble's capabilities and significantly cutting operating costs. Clervoy, the mission's flight engineer, proved his expertise as the main operator of the Shuttle's robotic arm, used during the space walks to manoeuvre astronauts around the Telescope in the Orbiter's payload bay.

The mission's prime objective was to replace HST's six gyroscopes (three of which must be working to meet the very precise pointing requirements). As well as replacing these gyros, the crew also replaced other equipment on Hubble that had either degraded in the harsh environment of space or could be replaced with more up-to-date technology.

HST had been out of operation since a fourth gyroscope had failed in November. European astronomers therefore breathed a collective sigh of relief as the giant orbiting observatory was gently eased back into space at the end of the busy eight-day servicing mission. esa

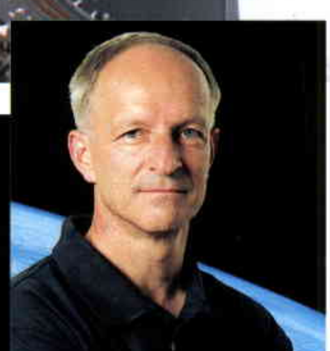


HST in the Shuttle cargo bay on 21 December 1999



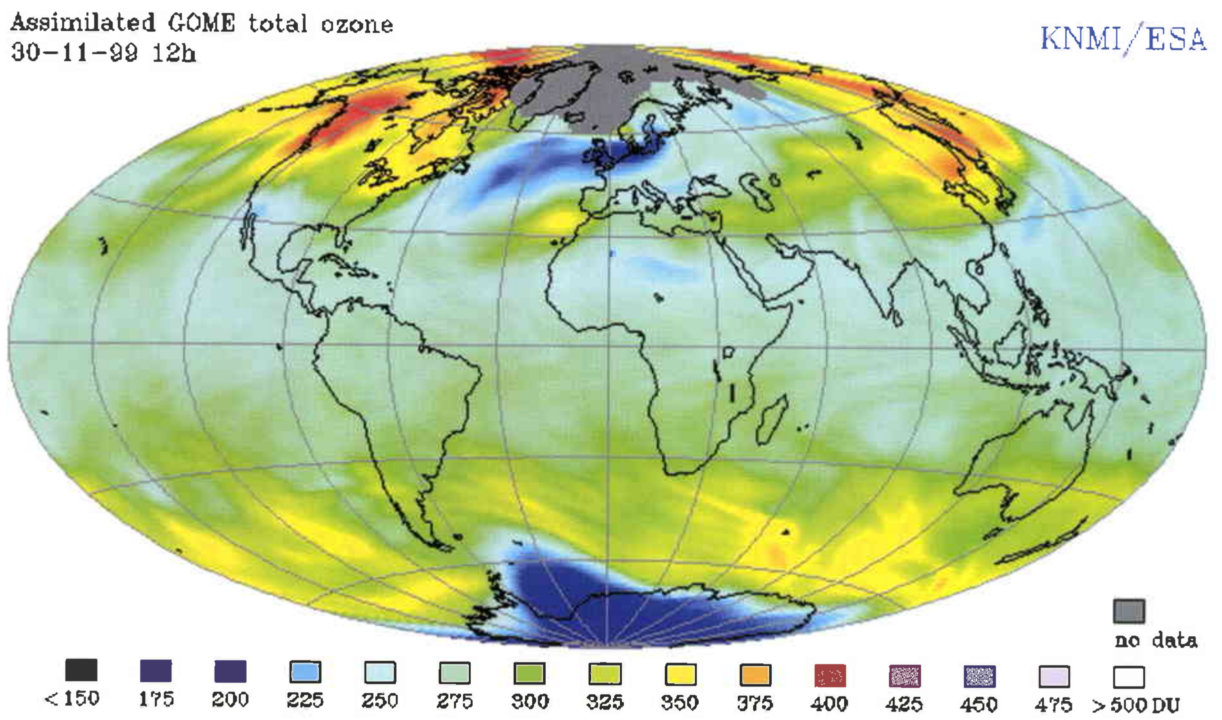
'Discovery' on the launch pad

Photo: J-C. Le Floc'h



Claude Nicollier

Jean-François Clervoy



Low Ozone Levels Detected Over Europe

On 30 November, ESA's ever-vigilant ERS-2 remote-sensing satellite detected abnormally low ozone levels over parts of Northwestern Europe. Levels over Belgium, The Netherlands, Scandinavia and the United Kingdom were nearly as low as those normally found in the Antarctic. Individual point measurements made from the ground in The Netherlands confirmed that local values were indeed some 30% below normal levels for that time of year.

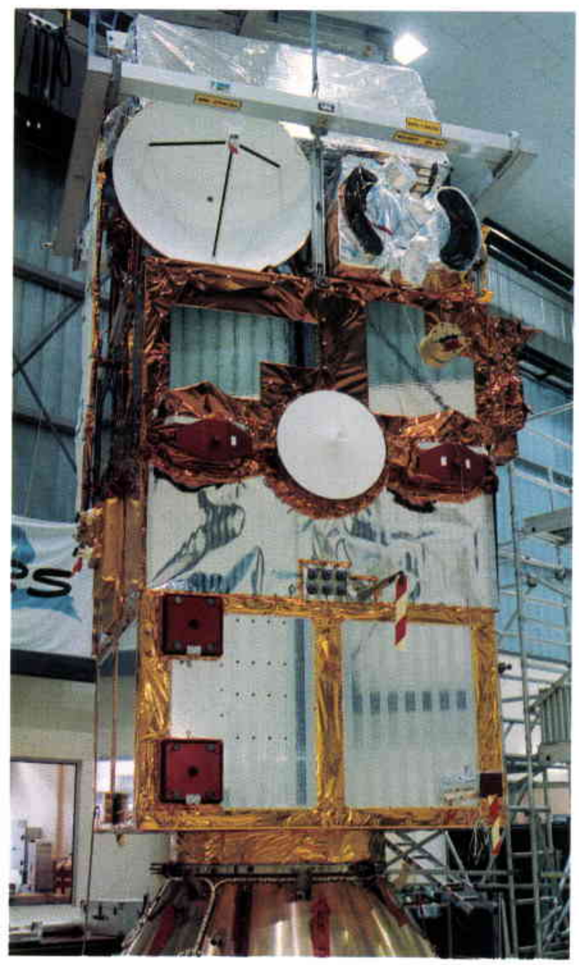
The ozone layer protects our planet from potentially harmful ultraviolet sunlight. Any thinning in the layer results in an increase in the amount of radiation getting through. At this time of the year and at these latitudes, however, the Sun does not rise far enough above the horizon to deliver a significant amount of harmful radiation.

Scientists worldwide are studying the exact causes of these 'local' ozone lows, the last of which was detected in 1997. They know that they are often associated with exceptionally low temperatures in the lower stratosphere and the presence of polar stratospheric clouds, which contain catalysts that speed up the chemical reactions that destroy ozone.

Since ERS-2's launch in 1995, Europe has been equipped with its own spaceborne ozone-monitoring instrument, the Global Ozone Monitoring Experiment (GOME). Teams of European experts have been using GOME to produce daily maps of the global ozone layer, and making them available to the public on the World-Wide Web. This recent ozone low was first drawn to ESA's attention by a team working at the Royal Dutch Meteorological Institute (KNMI) in De Bilt (NL).

Europe is already preparing the next-generation of satellite instruments to improve further the monitoring of ozone and other key chemicals in our atmosphere. ESA's environmental satellite Envisat, designed and built by European industry, will be launched in 2001. It will carry three new scientific instruments to monitor atmospheric ozone, which will be even more powerful than those presently carried by ERS-2.

In addition, ESA and the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat) are preparing a series of three satellites (Metop) that will carry follow-on GOME instruments and will guarantee at least ten years of continued ozone monitoring from space from 2003 onwards. esa



ERS-2

First Viewing of Europe's Future Geostationary Meteorological Satellites

On 23 November 1999, the first flight model of Europe's Meteosat Second Generation (MSG) satellite was on display at the Cannes (F) facility of Alcatel Space, the Prime Contractor to ESA. MSG-1 is scheduled for launch in October 2000 on an Ariane vehicle.

The initial Meteosat system was developed by ESA soon after its formation and the first satellite in the series was launched in 1977. A further six Meteosats have since been launched, and in January 1987 the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat), five months after its own formation, took over formal responsibility for the Meteosat system.

This new geostationary meteorological satellite system is the result of the ensuing close cooperation between ESA and Eumetsat. The satellite's main feature is the Spinning Enhanced Visible and Infrared Imager (SEVIRI). Its 12 different spectral channels will provide 20 times more information than the current Meteosats, offering new and in some cases unique, capabilities in cloud imaging and tracking, fog detection, measurement of Earth-surface and cloud-top temperatures, tracking of ozone patterns, as well as many other improved data.

MSG will provide a new weather image every 15 minutes, instead of every 30 minutes as at present. The data-circulation system will also allow much higher data rates for both transmission (3.2 Mbps) and dissemination (1 Mbps). This, together with the enhanced imagery, will result in a dramatic increase in Europe's capabilities for monitoring weather patterns over the Atlantic Ocean, Europe and Africa, and for the prediction of, and issue of warnings for severe storms and other potentially hazardous meteorological phenomena.

The viewing of MSG-1 followed a Press Conference organised jointly by ESA, Eumetsat and Alcatel Space, during which key representatives from the three organisations presented a comprehensive overview of the satellite, including its development, benefits, user requirements, and future operations.

The MSG-1 flight model on display at Alcatel Space, in Cannes (F)

Europeans to Build Satellites for the Global Weather Watch

On 7 December 1999, ESA's Director General, Mr Antonio Rodotà , and the Director of the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat), Dr. Tillmann Mohr, signed a contract with Matra Marconi Space, represented by Mr Armand Carlier, its Chief Executive Officer, for the development and production of a series of three Metop satellites.

The first spacecraft of the series, which will be the first European polar-orbiting satellite dedicated to operational meteorology and climate monitoring, is scheduled for launch in 2003. It will circle the Earth at approximately 840 km altitude, compared with today's Meteosat weather satellites, first launched in the 1970s, which are in geostationary equatorial orbit at 36 000 km altitude. They will soon be replaced by the Meteosat Second Generation. The Metop satellites – designed by Matra Marconi Space (F), together with a pan-European industrial consortium which includes Daimler Chrysler Aerospace (D), Matra Marconi Space UK, and Alenia Aerospazio (I) – will provide complementary sounding and imagery data, with daily coverage of most of the globe.

Metop carries twelve instruments that will provide highly valuable information for meteorologists as well as Earth-science researchers. In addition to a suite of established instruments provided by the US National Oceanic and Atmospheric Administration (NOAA), an advanced Infrared Atmospheric Sounding Interferometer (IASI) is being developed in Europe which will significantly enhance Metop's measuring capabilities compared with existing polar-orbiting satellites. Another 'first' is the ESA-developed GRAS instrument, a sounder based on the occultation of GPS radio signals by the Earth's atmosphere. Metop will also carry a five-channel Microwave Humidity Sounder (MHS), directly procured by Eumetsat.

Other European instruments on Metop are new to operational meteorological use, but have been flown on ESA's ERS satellites and used with great success by weather centres. The ESA-developed Advanced Scatterometer (ASCAT) instrument will provide key information about the winds over the Earth's ocean surfaces, and the improved Global Ozone Monitoring instrument (GOME-2) will measure the atmosphere's ozone content.

All in all, therefore, the new Metop data are expected to provide key information for the improvement of numerical weather-prediction systems. Metop forms part of the Eumetsat Polar System (EPS) programme, which includes the procurement of the three Metop satellites from ESA, their launches, the development of a ground segment, and the operation of the complete system over the programme's 14-year lifetime.

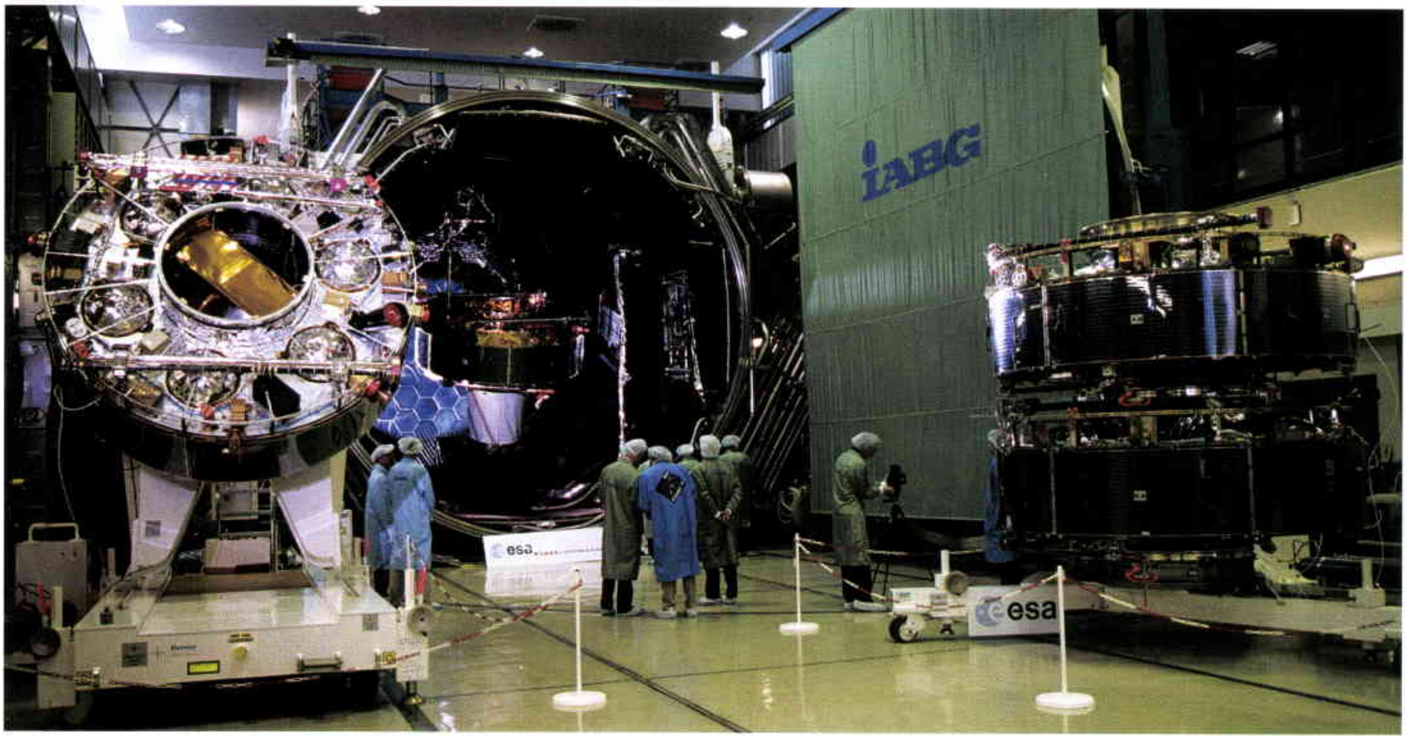
Dr. Tillmann Mohr (left), Director of Eumetsat, Mr Antonio Rodotà, ESA's Director General, and Mr Armand Carlier, Chief Executive Officer of Matra Marconi Space

Cluster-II Quartet on Stage Together

Visitors to the test and integration facilities at IABG, Munich (D), on 24 November could be excused for thinking they were suffering from multiple vision. On display in a giant clean room were the four identical Cluster-II spacecraft. This was the only occasion on which all four of these ESA spacecraft will be displayed together in Europe.

This unique event marked the final stages in the lengthy assembly and test programme, during which the individual spacecraft have been assembled in sequence. Two had already completed their assembly and systems testing and were about to be stored in special

The four Cluster-II spacecraft on show at IABG in Munich (D)



containers at IABG prior to shipment to the Baikonur launch site in Kazakhstan this spring. In the case of the other two flight models, installation of the science payloads had been completed, but their exhaustive series of environmental tests at IABG had yet to begin.

Following their delivery to the launch site in April, the satellites will be launched in pairs in June and July 2000. Two Soyuz rockets, each with a newly designed Fregat upper stage, are being provided by the Russian-French Starsem company. This will be the first time ESA satellites have been launched from the former Soviet Union.

Cluster-II is a replacement for the original Cluster mission, which was lost during the maiden flight of Ariane-5 in June 1996. ESA, given the mission's importance in its overall strategy in the domain of Sun-Earth connection investigation, proposed to rebuild this unique project. The ESA Member States supported that proposal, and on 3 April 1997 the Agency's Science Programme Committee agreed that Cluster-II should go ahead.

Construction of the Cluster and Cluster-II spacecraft has been a major undertaking for European industry. Built into each 1200 kg satellite are six propellant tanks, two pressure tanks, eight thrusters, 80 m of pipework, about 5 km of wiring, 380 connectors and more than 14 000 electrical contacts. All four spacecraft have been assembled at the Friedrichshafen plant of prime contractor Dornier Satellitensysteme. On completion, they were sent to IABG in Ottobrunn, near Munich, for intensive vibration, thermal vacuum and magnetic testing.

The European ground segment for the mission is just as important. A vast amount of data – equivalent to 290 million printed pages – will be returned to Earth over the mission's two-year lifetime. Signals to and from the spacecraft will be sent via a 15 m antenna at ESA's Villafranca facility in Spain and processed at the Agency's European Space Operations Centre (ESOC) in Darmstadt, Germany.

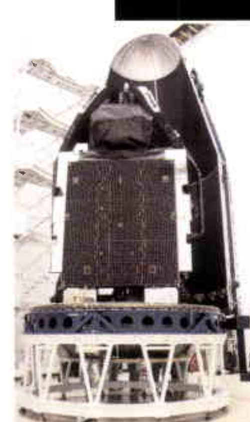
The Main Control Room at ESOC will be used during the launch and early phases of the mission, with teams of operators working around the clock. About two weeks after the second Cluster-II pair have been placed into their operational orbits, mission operations will switch to a smaller Dedicated Control Room at ESOC.

The Joint Science Operations Centre at Rutherford Appleton Laboratory in the United Kingdom will co-ordinate the scientific investigations. Its main task will be to combine all of the requirements from the 11 science instrument teams into an overall plan. The flow of information returned by the 44 instruments will be distributed to eight national data centres - six in Europe, one in the USA and another in China.

The Cluster-II mission will take place during a period of peak activity in the Sun's 11-year cycle, when sunspots and solar radiation reach a maximum. It will measure the effects of this activity on our near-Earth space environment as incoming energetic particles subject the magnetosphere – the region around the Earth dominated by its magnetic field – to a severe buffeting.

This will be the first space science mission ever to fly four identical spacecraft simultaneously. Once the quartet have been inserted into highly elliptical polar orbits, ranging from 19 000 to 119 000 km above the Earth, they will spend the next two years travelling from the magnetosphere into interplanetary space and back again.

"Cluster-II will give us the best information yet on how the Sun affects the near-Earth environment," says Project Scientist Philippe Escoubet. *"For the first time we will be able to study the Earth's magnetic field from four viewpoints with identical instruments. It will be like having four cameras at a football match - one behind the goal and three others at different angles. This is very exciting because it will help us to really understand the space environment which surrounds our planet."*



The Cluster-II mission, its science and operations will be described in detail in three articles in the next issue of the ESA Bulletin. esa

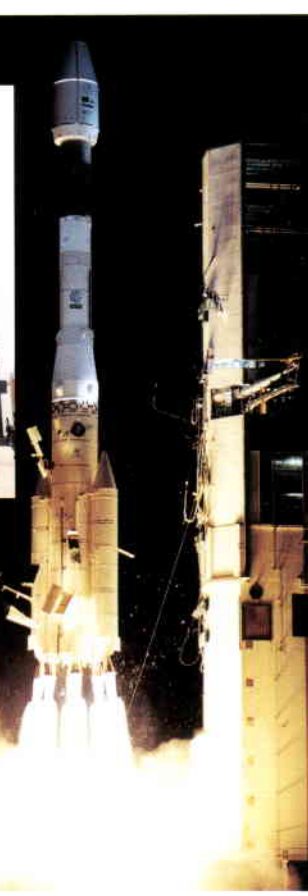
Ariane-4 Continues to Perform Flawlessly

The 124th Ariane launch (V124) took place successfully on 3 December 1999 at 13:22 p.m. Kourou time (16:22 p.m. GMT). An Ariane-40 vehicle without strap-on boosters, lifting-off from the European spaceport in Kourou, French Guiana, successfully placed the French Helios-1B satellite into a polar Sun-synchronous orbit.

Just 18 days later, the 125th Ariane launch (V125) lifted-off at 09:50 p.m. Kourou time on 21 December. The Ariane-44L, equipped with four liquid strap-on boosters, placed the American telecommunications satellite Galaxy XI into geostationary transfer orbit.

The 126th Ariane launch (V126), and the first of the new millennium, occurred on 24 January at 22:04 p.m. local time, when an Ariane 42L, equipped with two liquid strap-on boosters, lifted-off from Kourou carrying Galaxy XR into geostationary transfer orbit.

The 127th Ariane-4 launch (V127), at 22:04 p.m. Kourou time on 17 February 2000, put the telecommunications satellite Superbird-4 successfully into orbit. esa



Lift-off of Ariane V126 with Galaxy XR on board

A GPS-based Ocean Altimetry Experiment at ESTEC

An experiment to investigate the use of reflected Global Positioning System (GPS) signals for ocean altimetry was carried out at ESTEC (NL) in January 2000. The concept of using GNSS (Global Navigation Satellite System) reflected signals for ocean altimetry is already the subject of a European Space Agency patent (ESA Patent No. 321, 'PARIS Altimeter System', M. Neira, 1993). The purpose of this latest experiment was to test a new technique, called PIP (PARIS Interferometric Processor), based on carrier phase processing using several (at least two, optimally three) frequencies.

An upward-looking and a downward-looking antenna were suspended over a pond in the grounds of ESTEC. This antenna assembly was moved up and down with amplitudes varying from 1 m to a few centimetres. The goal was to retrieve the variation in height over the water of the antennas with centimetre accuracy using the PIP concept. First results are encouraging and detailed analysis is now in progress.

The novel ESA-developed PIP technique should allow ocean altimetry at the centimetre level in the future, by taking advantage of the multi-carrier signal structure of the future European GPS and Galileo navigation systems. The technique

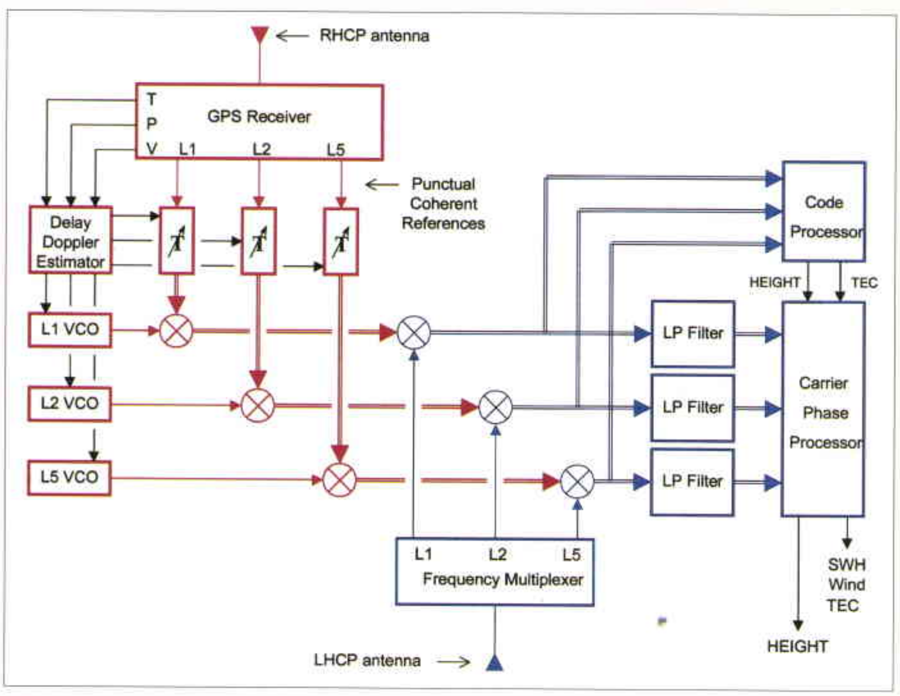
How it Works

With the PIP technique, the signals L1, L2 and L5 signals shown in the accompanying figure are received from a GPS satellite. Direct-path signals are received through an upward-looking antenna on-board a Low Earth Orbit (LEO) satellite. The signals reflected by the ocean surface are picked-up by a downward-looking antenna onboard the same satellite. The direct signals are processed by a GPS receiver, which provides time, position and velocity as well as punctual coherent references for each frequency and each GPS satellite.

For optimum performance, the three PIP frequencies must be properly spaced, with two carriers close together (L2 and L5) and the third (L1) further away - for example, the three future GPS civilian frequencies L1=1575 MHz , L2=1227 MHz and L5=1176 MHz. It is likely that Galileo will also transmit several carriers with similar spacings

The PIP processor's first operation is a complex down-conversion of the reflected-path GPS signals using a signal model (or replica). The replica of each reflected signal and each GPS satellite consists of a delay-Doppler-shifted version of the punctual coherent reference provided by the GPS receiver. The down-converted signals are the phase difference between the incoming reflected signals and their replicas. The phase differences of the reflected signals at L1, L2 and L5 are then low-pass-filtered to a specific bandwidth. The filter bandwidth is selected to ensure good signal-to-noise ratio and adequate spatial resolution, and takes into account the Doppler spread (typically 200-500 Hz) depending on GPS satellite elevation. The three filter outputs (one per frequency) can then be combined in different ways within a carrier phase processor to facilitate the retrieval of both ocean altimetry and ionospheric effects.

In a carrier phase wide-lane processor, the L1 and L2 filter outputs are routed into two phase detectors, which use the L5 filter output as reference signal, and further low-pass filtered. The two smoothed phase detectors provide the desired wide-lane phases, namely L1-L5 and L2-L5. For a flat ocean surface, the two wide-lane phases are constant and proportional to the path difference between direct and reflected signals, up to an integer number of wavelengths, and the thermal noise present in the measurement. For a GPS satellite at the zenith of the LEO satellite, one cycle of the L1-L5 or L2-L5 wide-lane phases corresponds to a height change of 0.37 or 3.0 m, respectively. A carrier phase accuracy of 1% results in height resolutions of 3.7 and 30 mm, respectively. When the ocean surface is rough, the phase of each frequency changes rapidly due to the Doppler spread, but the wide-lane phases change much more slowly, their average value being proportional to the path difference as before.



Block diagram of the PIP processor (the processing for only 1 satellite is shown)

For a slightly rough ocean surface, the deviation of the wide-lane phases with respect to their average value is small. As ocean surface roughness increases, so do the deviations of the short wide-lane (L1-L5) phases. When the standard deviation of the wave height is half the wide-lane wavelength, cycle ambiguity starts to occur (a phase deviation beyond one cycle). This point corresponds to a significant wave height of 1.5 m. The longer wide-lane phases (L2-L5) suffer a similar effect, but at a higher significant wave height of about 12 m, making this the most robust of the two phases for ocean altimetry.

By using an appropriate model, the temporal variation in the ionospheric effect along each reflected path can be retrieved from the short wide-lane in combination with the code-processor measurements. The altimetry retrievals using the long wide-lane can be corrected for temporal ionospheric variations in this way. The temporal variation in the ionosphere's total electron content and its absolute value are therefore byproducts of the PIP processor, along with wind and significant-wave-height data.

has been inspired by the Three Carrier Ambiguity Resolution (TCAR) concept being studied by the Agency in the context of Galileo for high-precision relative navigation. The key to TCAR lies in measuring the phase of the signals at different frequencies and combining them to form so-called 'wide-lane frequencies'. The integer ambiguity in the number of carrier cycles of each 'wide lane' can be resolved provided the noise at each step is small enough compared to the wavelength of that particular wide-lane combination. The final result is a range obtained with the accuracy of the carrier, typically at millimetre level. PIP differs from TCAR in that it handles signals reflected from the ocean, which have the usual characteristics of a radar return produced by a distributed target, namely they remain coherent over a short period but suffer large amplitude variations.

The experiment set-up at ESTEC

Europe Prepares for a Common Space Strategy

Ms Loyola de Palacio del Valle Lersundi, EU Commissioner for Transport and Energy, and Mr Philippe Busquin, EU Commissioner for Research, visited ESA's Research and Technology Centre, ESTEC, in Noordwijk (NL) on 7 February. Their discussions with ESA's Director General Antonio Rodotà and senior management touched on matters of common interest, such as a European space strategy and the Galileo satellite navigation programme, and on monitoring hazardous cargo movements at sea.

The European Commission and ESA have already started elaborating a joint European space strategy, following Ministerial Resolutions adopted by their respective Councils last year calling for them to complete this by the end of 2000. Close consultation with all interested parties in Europe will take place over the coming months to provide inputs. Mr Busquin emphasised the importance of coordination in European research, as elaborated in his latest communication 'Towards a European Research Area'.

Galileo is a joint EU/ESA initiative to develop a European global satellite navigation system. The programme is currently in the detailed definition phase. Once completed, Galileo will provide an autonomous European traffic management and telematics infrastructure, generating valuable economic benefits for European equipment manufacturers and service industry providers and creating many jobs. Under current plans, the system will comprise at least 21 satellites (in medium Earth orbit at 24 000 km, possibly supplemented by geostationary satellites at 36 000 km) and the associated ground infrastructure. Ms de Palacio highlighted the importance of this programme, which is an essential contribution to developing an integrated European transport policy, to be confirmed by the EU Council by end-2000.

The Commissioners also showed interest in a new initiative proposed by Mr Rodotà involving harnessing space technology to monitor hazardous-cargo movements at sea and conduct research on oil spill detection to improve management of the environment. Positioning equipment is to be installed on cargo for the operational tracking of oil tankers and other vessels carrying hazardous materials. This will be included as a testbed activity within the Galileo programme. This initiative will also serve in drawing up and enforcing European legislation in this area and in increasing transportation safety. It will also assist decision-making on ship routing/planning and help in preparing/updating coastal-zone sensitivity maps.

From left to right: Mr Antonio Rodotà, Mr Philippe Busquin, Ms Loyola de Palacio del Valle Lersundi, Mr Alain Bensoussan (Chairman of ESA Council), Mr Jean-Jacques Dordain (ESA's Director of Strategy and Technical Assessment) and Mr Alexandre Popovitch (ESTEC Testing Division)

Ariane-5 / XMM Launch

Following the successful Launch Readiness Review for the XMM (X-ray Multi-Mirror Mission) scientific satellite, which took place in Kourou, French Guiana on 7 December 1999, ESA's Director of Scientific Programmes, Prof. Roger Bonnet, communicated the green light for the launch. The countdown sequence for this first commercial flight of Ariane-5 had been finalised following the dress rehearsal on 6 December, and on 9 December the launcher began its journey from the final assembly building (see accompanying photographs) to the launch pad. The rollout, which began at 11:00h local time and took several hours, was watched by the ESA and Arianespace teams, invited guests and press representatives. Among the guests were the 14 children – one from each ESA Member State – whose designs are incorporated in the new XMM logo, which was proudly displayed on the Ariane-5 fairing.

The copybook launch took place at 15:32h Paris time on 10 December. Within an hour of lift-off, ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany, confirmed that XMM was safely under its control, with the requisite electrical power available from the spacecraft's solar arrays. XMM's initial orbit carried it far out into space, to 114 000 km from the Earth at its most distant point or apogee, with its closest approach, or perigee, at 850 km distance. The next phase in the spacecraft operations, about a week later, was to raise the perigee to 7000 km by repeatedly firing XMM's own thrusters. This final operating orbit maximises the time that the spacecraft spends – 40 h of each 48 h orbit – clear of the radiation belts that impede our view of the X-ray Universe from Earth.

On 17/18 December, the telescope doors on the X-ray Mirror Modules and on the Optical Monitor telescope were opened for the first time. The Radiation Monitor was activated on 19 December, and the spacecraft was then put into a safe mode over the Christmas and New Year period.

The mission's scientific data is being received, processed and dispatched to astronomers by the XMM Science Operations Centre in Villafranca, near Madrid (E). Operations with the spacecraft restarted there on 4 January when, as part of the Commissioning Phase, all of XMM's scientific payloads were switched on one after the other for initial verifications.

By the week of 17 January, functional tests had begun on the Optical Monitor, the EPIC PN, the two EPIC MOS and the two RGS instruments. The internal doors of the EPIC cameras were opened whilst keeping the camera filter wheels closed. The commissioning images confirmed that the XMM spacecraft and its scientific instruments were functioning perfectly, to the great satisfaction of all involved.

The development of the four complex scientific instruments on XMM has been led by European scientists, with participation from institutes worldwide. Prime scientific objectives for XMM are to find out exactly what goes on in the vicinity of black holes, and to help clear up the mystery of the stupendous explosions called gamma-ray bursts. Other hot topics for investigation include 'cannibalism' among the stars, the release of newly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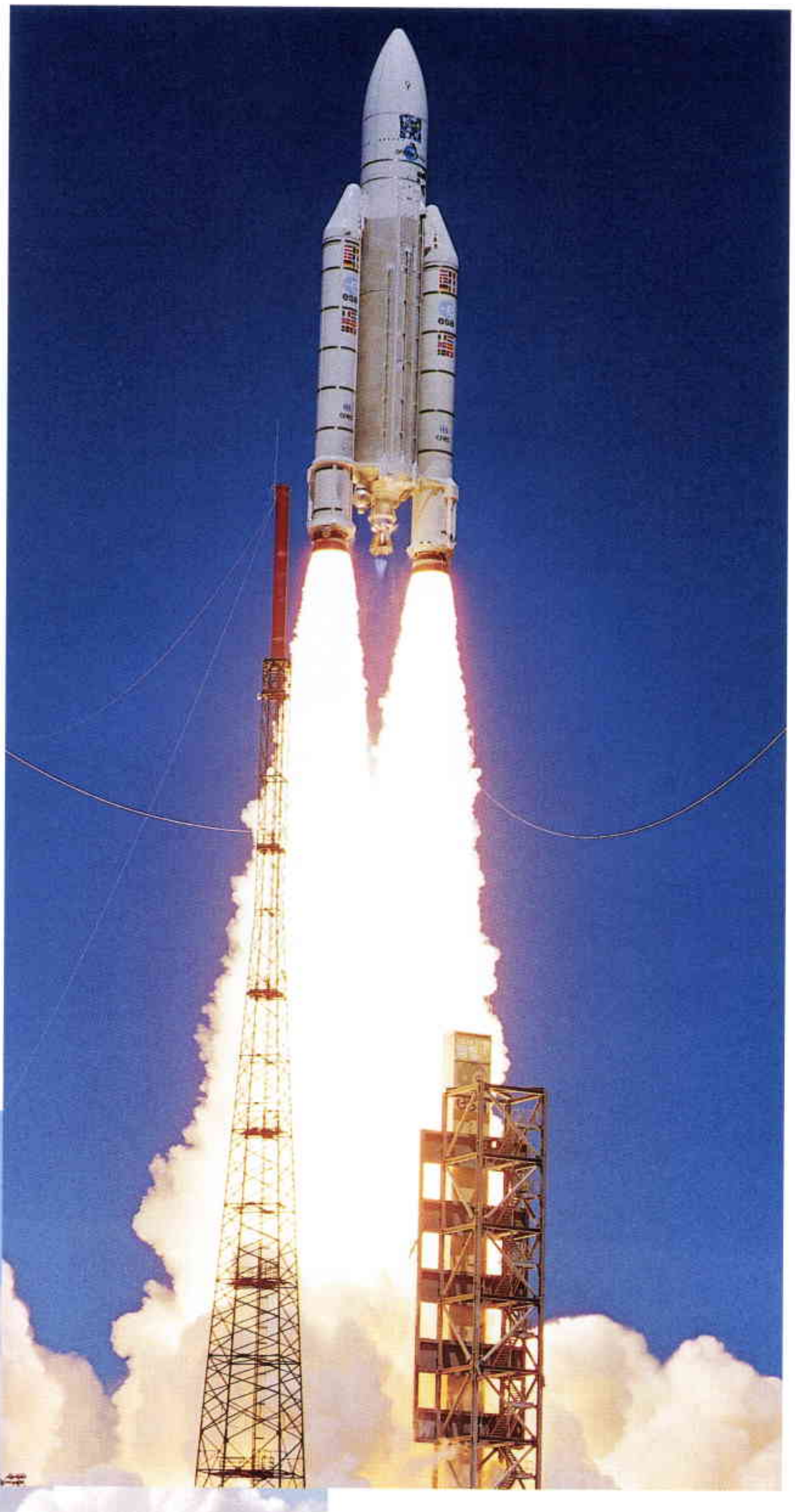

made chemical elements from stellar explosions, and the origin of the cosmic rays that rain down on the Earth.

In building the XMM spacecraft, the prime contractor Dornier Satellitensysteme in Friedrichshafen, Germany (part of DaimlerChrysler Aerospace) has led an industrial consortium involving 46 companies in 14 European countries and one US company.

Astounding first images

After initially making a series of engineering exposures, all three EPIC cameras were used in turn, between 19 and 24 January, to take several views of two different extragalactic regions of the Universe. These views, featuring a variety of extended and X-ray point sources, were chosen to demonstrate the full functioning of the observatory. The Optical Monitor also simultaneously viewed the same regions. One RGS spectrometer obtained its first spectra on 25 January; the other was commissioned at the beginning of February.

This initial series of short- and long-duration exposures have delighted the project team and the participating scientists. First analyses confirm that the XMM spacecraft is extremely stable, the telescopes are focusing perfectly, and the EPIC cameras, Optical Monitor and RGS spectrometers are working exactly as expected. The XMM Science Operations Centre is also performing well. Initial inspection of the first commissioning images immediately showed some unique X-ray views of celestial objects, several of which were presented to the media at a Press Conference at Villafranca on 9 February.

EPIC-PN false-colour X-ray image of the 30 Doradus region in the Large Magellanic Cloud

Credit : The EPIC consortium, ESA
The EPIC PI is Dr. M. Turner, Leicester University, UK. The EPIC-PN camera was built by MPE, Garching, Germany
EPIC Participating Institutes:
- Leicester University, UK
- Birmingham University, UK
- MPE, Garching, Germany
- IAAT, Tübingen, Germany
- IFC G. Occhialini, Milan, Italy
- TESRE, Bologna, Italy
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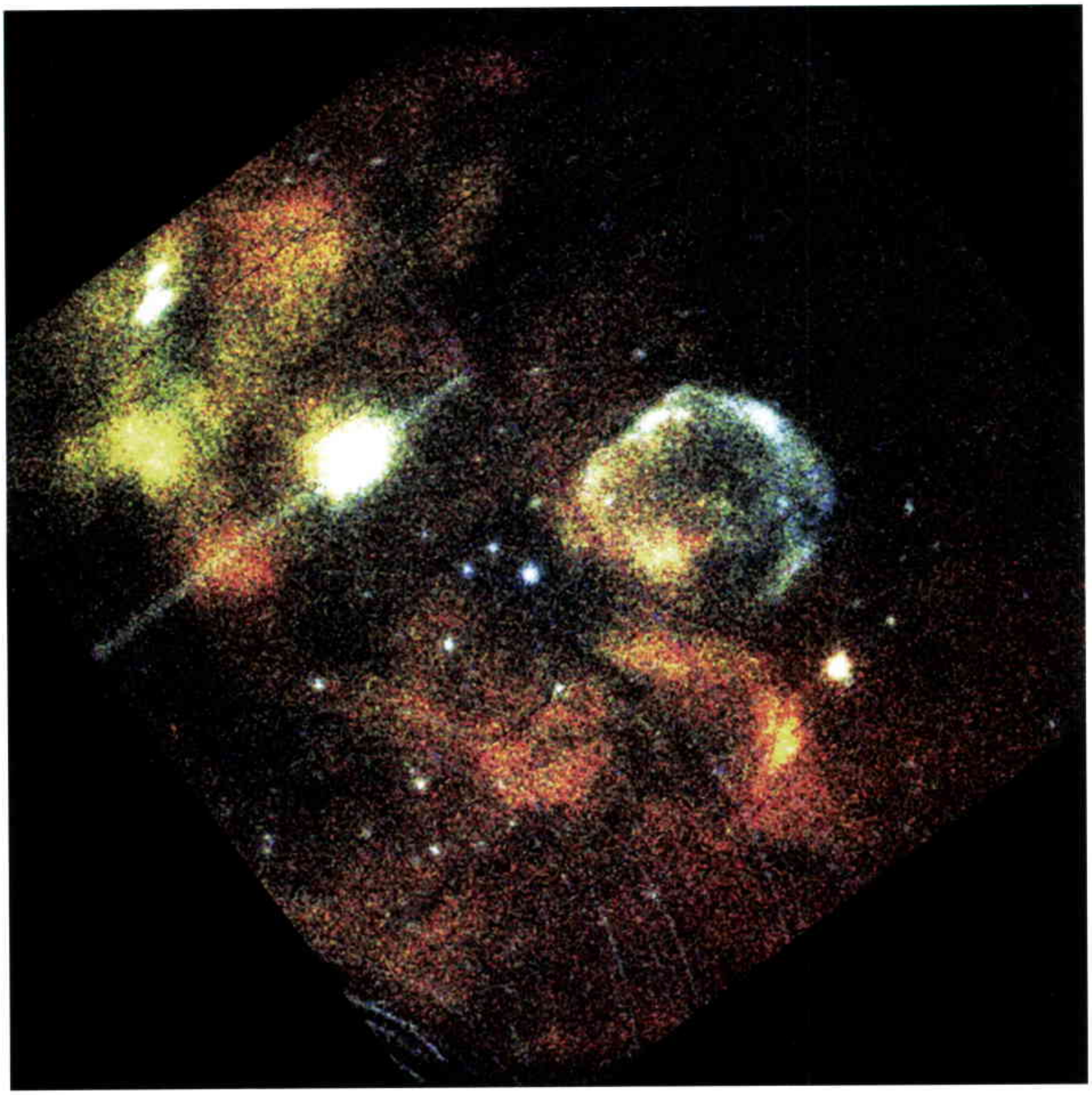

The Press Conference agenda included an introduction to ESA's past and future scientific projects by Roger Bonnet, ESA's Director of Scientific Programmes, and a review of the current status of the XMM spacecraft and its instruments, and future scientific expectations from the mission, by Dr. Fred Jansen, the ESA XMM Project Scientist.

At the same Press Conference, Roger Bonnet launched the third XMM 'Stargazing' Competition, directed at Europe's 16 to 18 year olds. Through this competition, these teenagers will be offered a unique opportunity to win observing time using XMM's X-ray telescope.

The Calibration and Performance Verification phase for XMM's scientific instruments begins on 3 March, with routine science operations planned to start in June.

Further information

A series of articles providing a detailed overview of the design and manufacture of the XMM spacecraft, its scientific payload and mission operations appeared in the previous issue of ESA Bulletin (No. 100, December 1999), which is available in hard copy from ESA Publications Division or in PDF format via the Publications Division's web site at:

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EPIC-MOS X-ray image, zoomed in to a bright supernova remnant in the Large Magellanic Cloud

Credit : The EPIC consortium, ESA
The EPIC PI is Dr. M. Turner, Leicester University, UK.
EPIC Participating Institutes:
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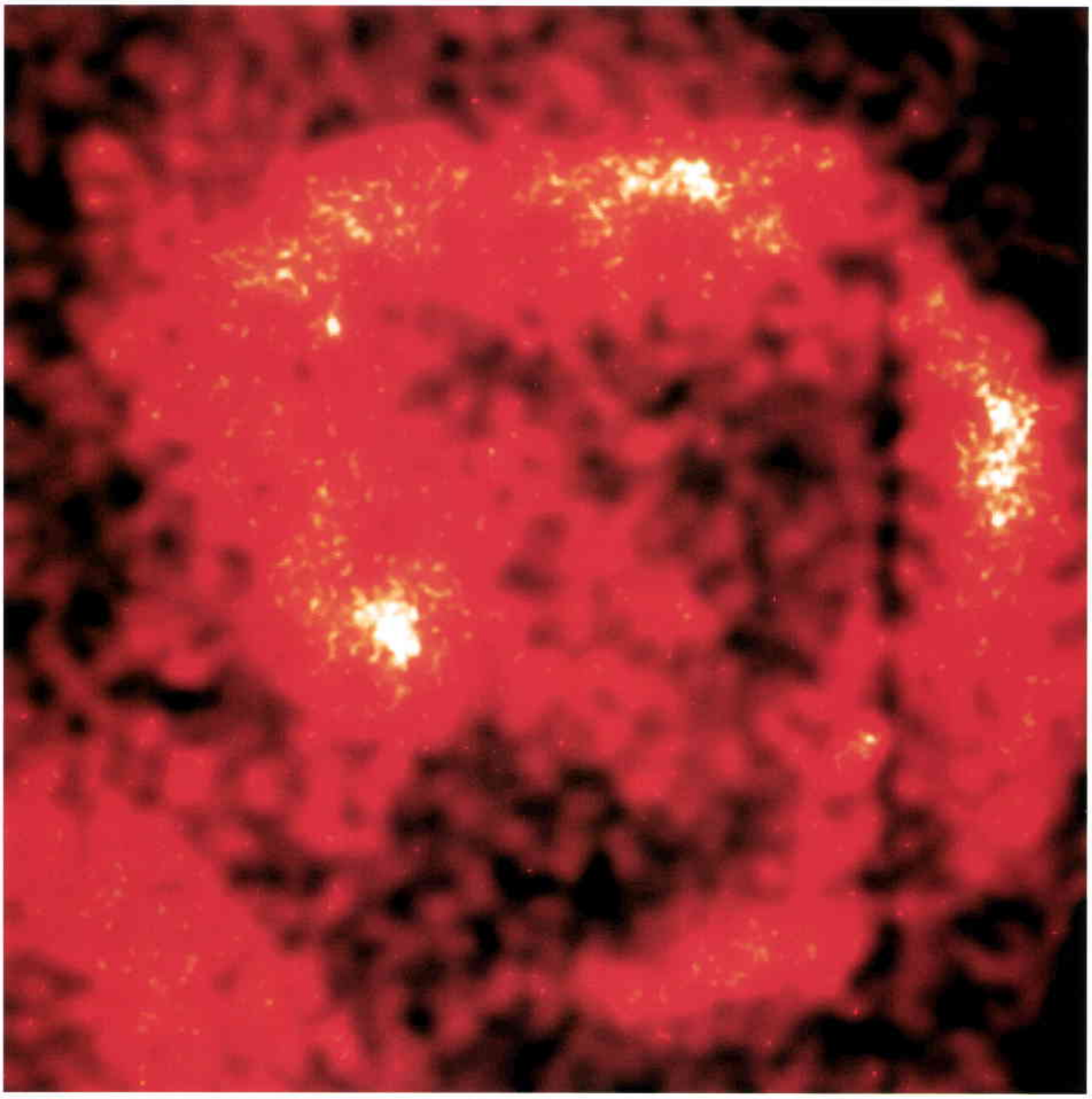

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WILSON A. & KALDEICH B. (EDS.)
NO CHARGE

PREPARING FOR THE FUTURE, VOL. 9 NO. 3 (DECEMBER 1999)
BRISSON P. (ED. M. PERRY)
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ECSL NEWS, NO. 20 (DECEMBER 1999)
HERMAN T. (ED. B. BATTRICK)
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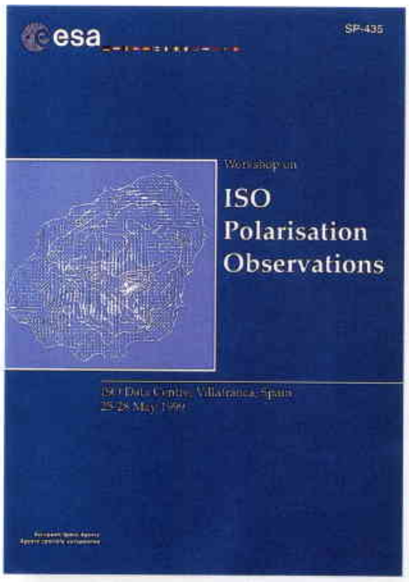

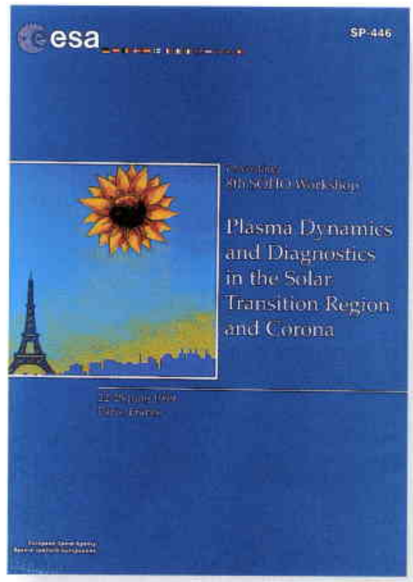

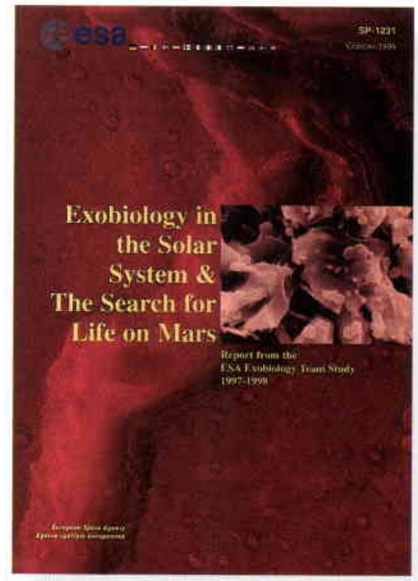

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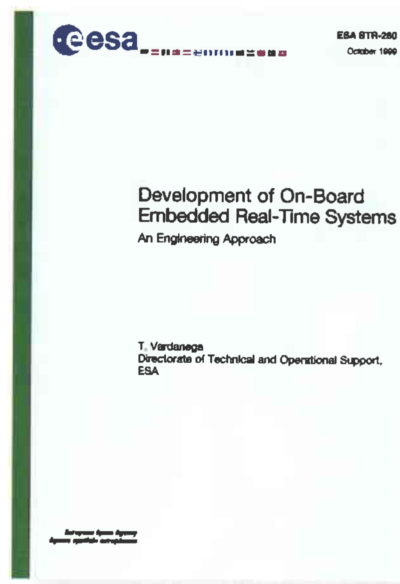

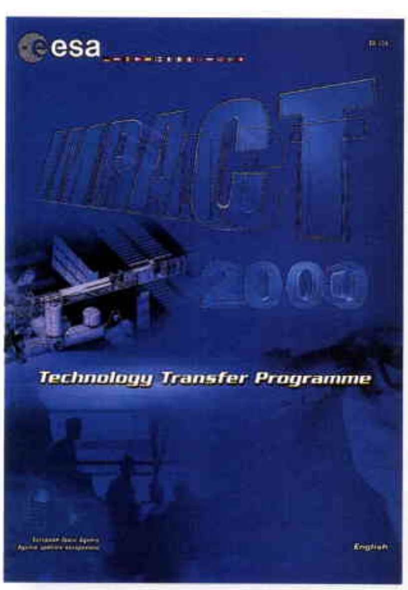

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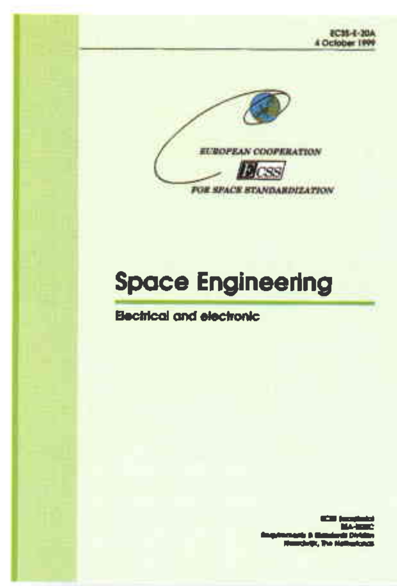

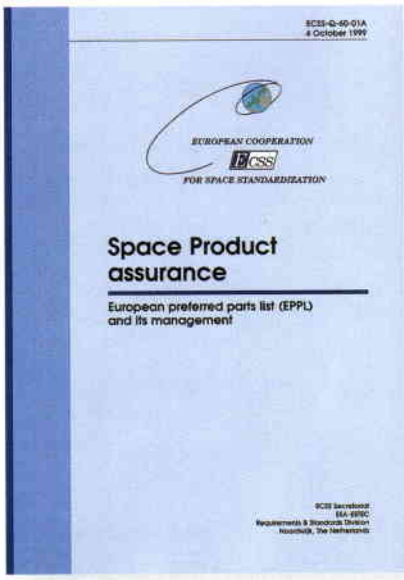

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