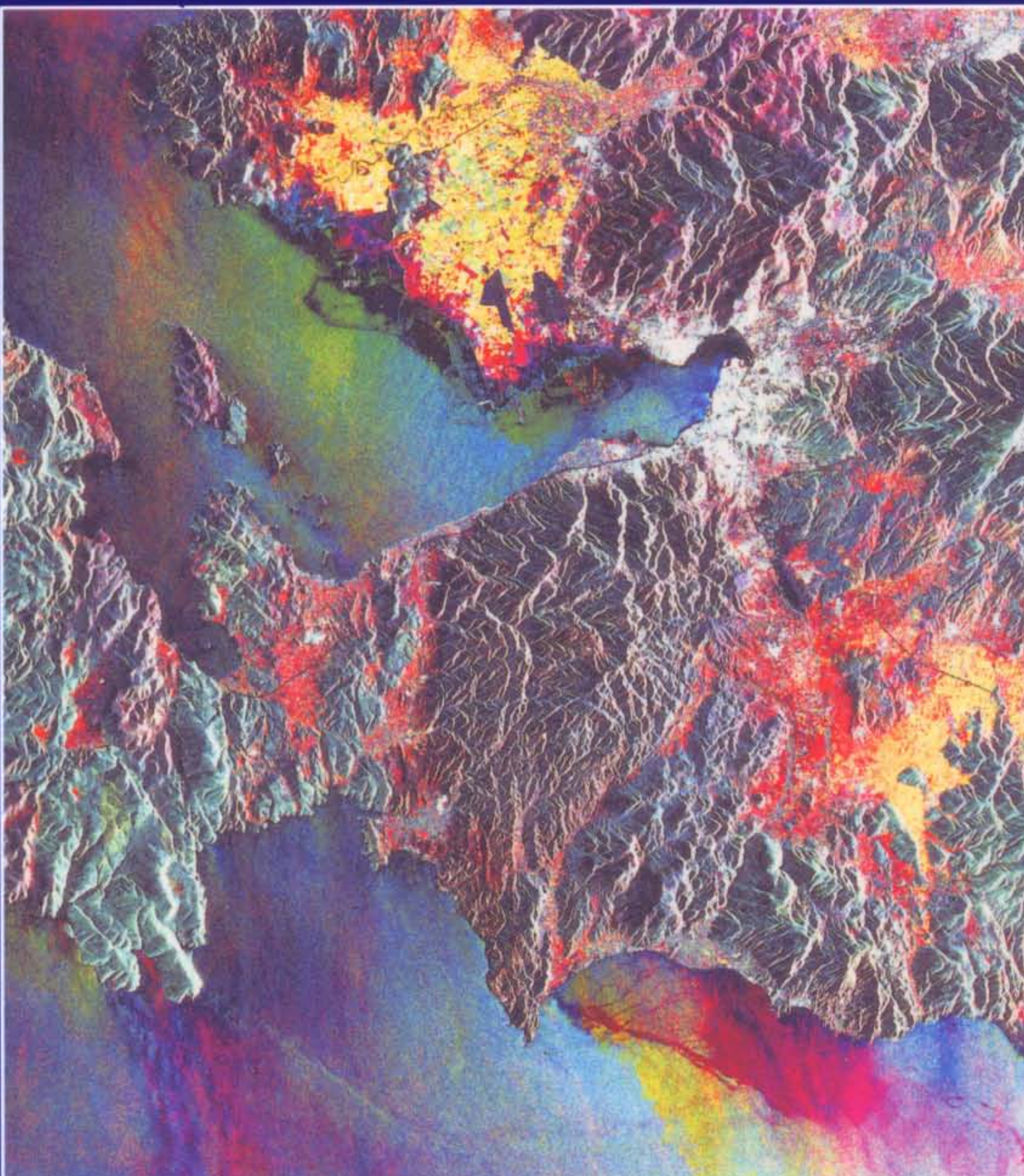
esa bulletin

number 87 - august 1996



European Space Agency
Agence spatiale européenne

european space agency

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

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

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agence spatiale européenne

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

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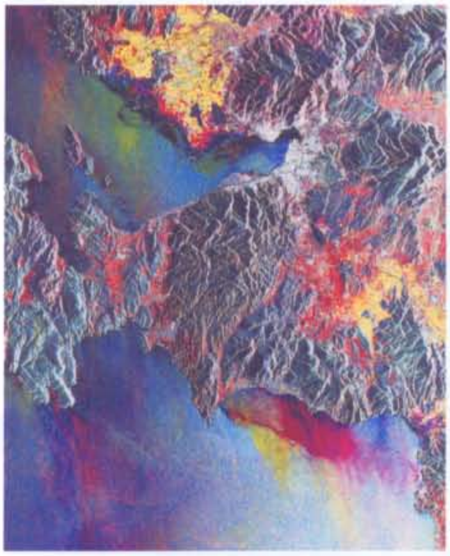

Cover: Izmir, Turkey as seen by ERS-1 and 2; see page 118

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Printed in The Netherlands ISSN 0376-4265

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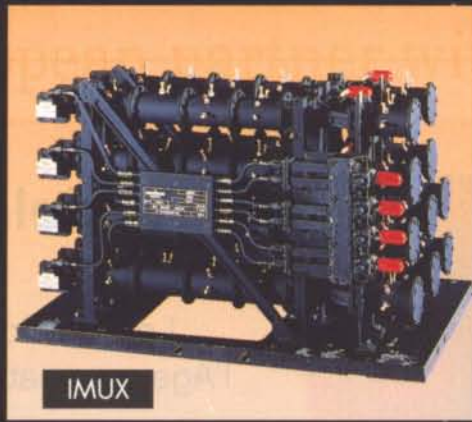
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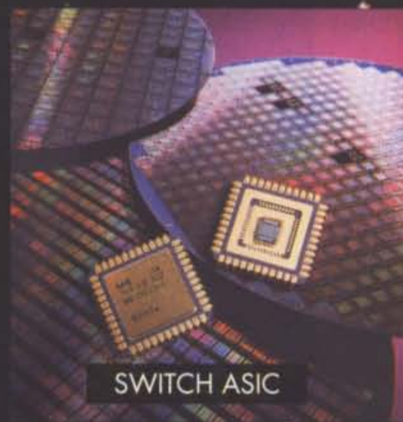
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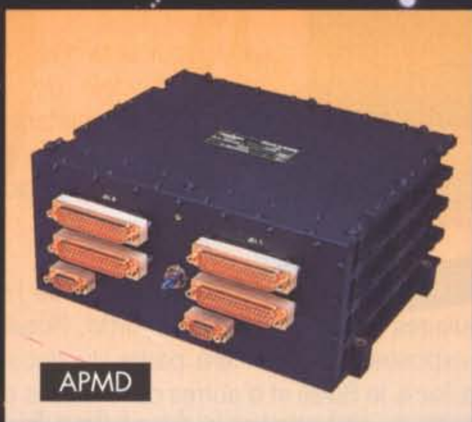
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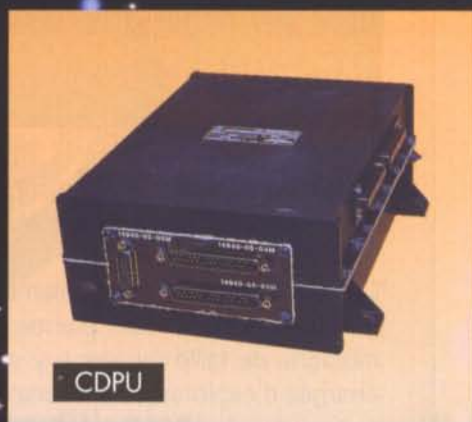
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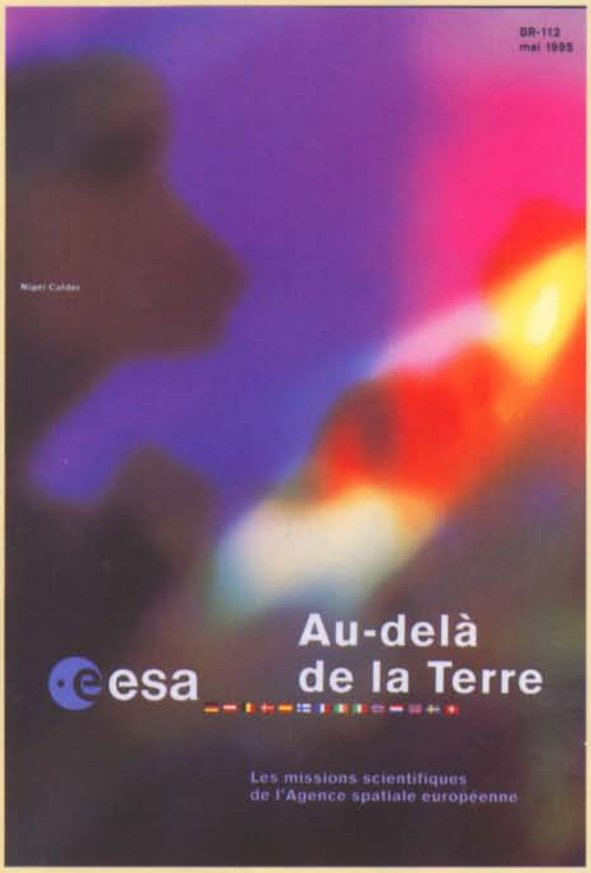


Au-delà de la Terre

Les missions scientifiques de l'Agence spatiale européenne (ESA)

de Nigel Calder

'Au-delà de notre ciel teinté de bleu par l'atmosphère terrestre s'étend l'Univers, ce vide spatial noir ponctué de planètes, d'étoiles et de galaxies. C'est le royaume des chercheurs spatiaux.'

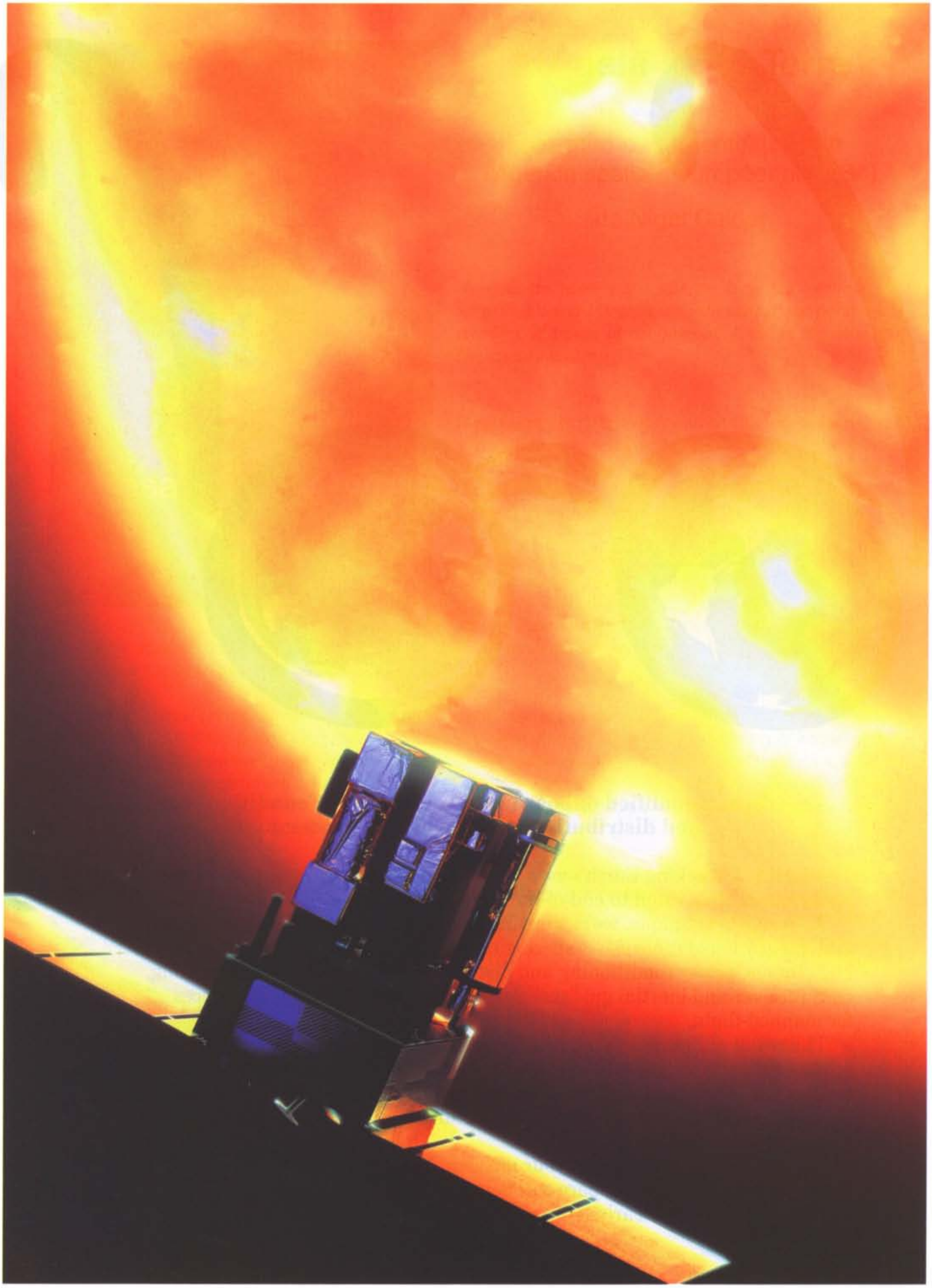
Nigel Calder, écrivain très connu en Grande-Bretagne pour la qualité de ses écrits scientifiques, brosse ici un tableau complet et vivant du programme de recherche spatiale de l'ESA, en nous donnant un avant-goût des projets que l'Agence compte mettre en oeuvre au XXI^e^ siècle.

La vigueur et la diversité de cette recherche s'imposent au lecteur. *Au-delà de la Terre* présente douze missions différentes, en mettant l'accent sur les raisons humaines et scientifiques qui sous-tendent l'immense travail à la clé de la recherche spatiale. La description proprement dite des missions est accompagnée de détails techniques apparaissant sous forme de tableaux et d'illustrations.

Cet ouvrage traite principalement du programme scientifique actuel de l'Agence : Horizon 2000. Les quatre grandes missions dites pierres angulaires — Soho et Cluster, XMM, Rosetta, First — ainsi que les différentes missions de taille moyenne y sont exposées. La première partie du document porte sur les engins spatiaux chargés d'explorer les environs de la Terre, le Soleil et d'autres destinations du système solaire, la deuxième étant consacrée aux télescopes d'astronomie sur orbite terrestre. Dans l'un et l'autre cas, l'auteur donne un aperçu du contexte historique et international dans lequel s'inscrivent les missions.

La troisième partie du document projette le lecteur dans la deuxième décennie du XXI^e^ siècle et traite plus particulièrement des trois grandes missions du programme Horizon 2000 Plus de l'ESA, qui couvre la période 2006-2016. Explorer la mystérieuse planète Mercure, exploiter les avantages de l'interférométrie pour atteindre un degré de précision inégalé dans le domaine de l'observation astronomique, partir à la recherche des ondes gravitationnelles — tels sont les trois projets majeurs de l'Agence pour cette période, conciliant les nécessités de la planification à long terme et le caractère imprévisible de la recherche.

Document disponible auprès de:	ESA/Division des Publications ESTEC Postbus 299 2200 AG Noordwijk Pays-Bas Fax : (31)71.565.5433	Prix:	35 florins (ou l'équivalent dans une autre monnaie, à régler soit en espèces soit par chèque libellé à l'ordre de 'ESA Publications Divisions')



The First Results from SOHO

V. Domingo, B. Fleck
ESA Space Science Department at NASA/GSFC, Greenbelt (MD), USA

A. Poland
Laboratory for Astronomy and Solar Physics, NASA/GSFC, Greenbelt (MD), USA

and **The SOHO Instrument Teams**

SOHO, launched by an Atlas II-AS from Cape Canaveral on 2 December 1995, was inserted into its halo orbit around the L1 Lagrangian point on 14 February, six weeks ahead of schedule. The launch and the orbital manoeuvres were so accurate and efficient that sufficient fuel remains on board to maintain the halo orbit for more than a decade, i.e. for at least twice as long as originally foreseen.

Already during their commissioning phase, the SOHO experiments have returned a wealth of data, impressive in terms of both its quality and diversity. Some of the images can be viewed via the SOHO pages (http://sohowww.nascom.nasa.gov) on the World Wide Web, and on the individual experiment pages, all with links from the SOHO home page.

Typical examples of the unique results being obtained with SOHO's instruments are presented here. Although they have been obtained with single instruments, it is worth noting that the main scientific advances from SOHO are expected to come from the joint analysis of coordinated observations.

Introduction

The Solar and Heliospheric Observatory, SOHO, is an international cooperative project between ESA and NASA to study the Sun. This space-based Observatory is viewing and investigating the Sun from its deep core, through its outer atmosphere – the 'corona' – and the domain of the solar wind, out to a distance ten times beyond the Earth's orbit. The spacecraft provides a highly-stabilised platform for a complement of twelve sophisticated, state-of-the-art instruments, developed and furnished by twelve international consortia involving 39 institutes from fifteen countries (Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Netherlands, Norway, Russia, Spain, Switzerland, the United Kingdom, and the United States).

Three helioseismology instruments are providing unique data for the study of the structure and dynamics of the solar interior, from the very deep core to the outermost layers of the convection zone. A set of five complementary remote-sensing instruments, consisting of extreme-ultraviolet (EUV), UV and visible-light imagers, spectrographs and coronagraphs, are currently giving us our first comprehensive view of the outer solar atmosphere and corona, leading to a better understanding of the enigmatic coronal heating and solar-wind acceleration processes. Finally, three experiments complement the remote-sensing observations by measuring the composition and energy of the solar wind and energetic particles at the spacecraft (Table 1).

The solar interior

Just as seismology reveals the Earth's interior by studying earthquake waves, solar physicists are probing the solar interior by the use of helioseismology. Oscillations detectable at the Sun's visible surface are due to sound waves reverberating through its stellar interior. Using seismology techniques and wave measurements from SOHO's Michelson Doppler Imager (MDI), which records the vertical motion of the Sun's surface at a million different points once a minute, SOHO's investigators have already been able to generate the first maps of horizontal and vertical flow velocities, as well as sound-speed variations, in the convection zone just below the Sun's visible surface (Fig. 1). The convection zone lies directly beneath the photosphere, which forms the visible surface and effectively hides what is below. As a result, very little is known about the convection zone's internal structure, despite the fact that it is the source of sunspots, solar flares and most other forms of solar activity that affect the Earth.

MDI data have been used to calculate the time it takes for sound to travel between many different points on the solar surface. Because the paths of these sound waves loop down

Table 1. The SOHO scientific instruments*

Investigation		Principal Investigator
GOLF	Global Oscillations at Low Frequencies	A. Gabriel, IAS, Orsay, France
VIRGO	Variability of Solar Irradiance and Gravity Oscillations	C. Fröhlich, PMOD Davos, Switzerland
MDI/SOI	Michelson Doppler Imager/Solar Oscillations Investigation	P. Scherrer, Stanford University, USA
SUMER	Solar Ultraviolet Measurements of Emitted Radiation	K. Wilhelm, MPAe Lindau, Germany
CDS	Coronal Diagnostic Spectrometer	R. Harrison, RAL, Chilton, UK
EIT	Extreme-Ultraviolet Imaging Telescope	J.-P. Delaboudinière, IAS, Orsay, France
UVCS	UltraViolet Coronagraph Spectrometer	J. Kohl, SAO, Cambridge, USA
LASCO	Large Angle Spectroscopic Coronagraph	G. Brueckner, NRL, Washington, USA
SWAN	Solar Wind Anisotropies	J.-L. Bertaux, SA, Verrières, France
CELIAS	Charge, Element and Isotope Analysis System	P. Bochsler, Univ. Bern, Switzerland
COSTEP	Comprehensive Supra Thermal and Energetic Particle Analyser	H. Kunow, Univ. Kiel, Germany
ERNE	Energetic and Relativistic Nuclei and Electron Experiment	J. Torsti, Univ. Turku, Finland

* IAS: Institut d'Astronomie
PMOD: Physikalisch-Meteorologisches Observatorium Davos
MPAe: Max-Planck-Institut für Aeronomie
RAL: Rutherford Appleton Laboratory
SAO: Smithsonian Astrophysical Observatory
NRL: Naval Research Laboratory
SA: Service d'Aeronomie

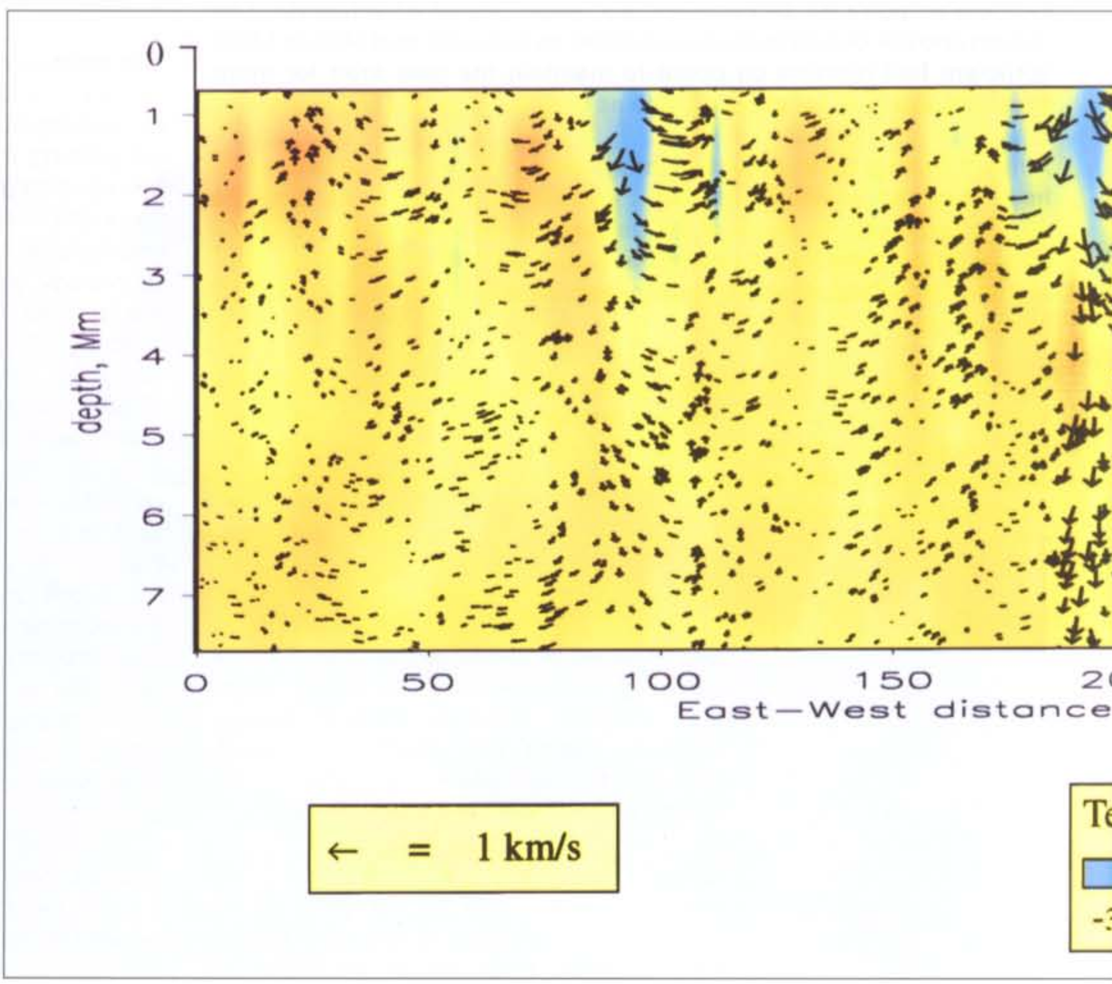
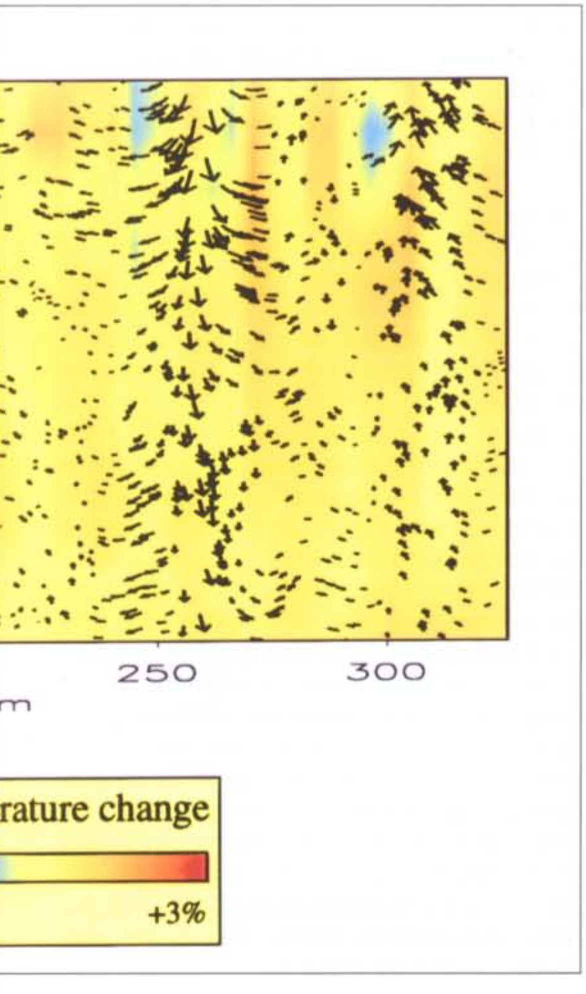


Figure 1. A vertical cut through the outer 1% of the Sun, showing flows and temperature variations inferred by helioseismic tomography using measurements from SOHO's Michelson Doppler Imager (MDI). The arrows indicate directions and relative speeds of the vertical motions within the Sun. Colour shading indicates temperature changes.

into the solar interior, one can use this information to map the temperature and flow patterns beneath the surface, similar to techniques used in computer-aided tomography to produce CAT scans.

Figure 1 provides a tantalising first view of how the convection zone is organised internally. For example, this map provides the first direct evidence for the depth of the features called 'granules', which cover the face of the Sun and are typically about 1500 km across. These granules are typically organised into larger domains called 'supergranules' that average about 25 000 km across. Theoretical calculations predicted that supergranule thicknesses should be between 25 and 30 percent of their width. The MDI mapping effort, however, suggests that they are shaped more like pancakes, with thicknesses only one-tenth of their width.

More significantly, the new map shows no evidence of the giant convection cells that had been predicted by a popular theory called the Global Circulation Model. It does, however, show evidence of narrow plumes of cooler gases streaming downwards towards the boundary with the radiative layer – a feature consistent with the results of some numerical simulations of the region. Surprisingly, however, the plumes appear to originate from the middle of the supergranules, rather than at their edges as had been proposed. Additional observations at other times and locations are needed to determine whether the features that the map reveals are representative. Future observations will also allow the researchers to make a 'movie' of this part of the convection zone so that they can observe how its structure changes over time.



Random motions on the Sun, due to convection and other dynamic activity, lead to a continuum of frequencies (i.e. a noise spectrum) when the measured surface velocities are Fourier-analysed. This presumed solar background level imposes the eventual limit for the detection of weak g-mode oscillations.

It is possible to model this noise spectrum, by making assumptions about the physical properties of the various sizes of convection cells and their distribution. The result of a tentative model based upon the combined effects of granulation, mesogranulation, super-granulation and active regions, integrated over the complete solar disc, is given in the same format as the spectrum actually observed by SOHO's GOLF instrument, or with the ground-based networks IRIS (Installation d'un Reseau International de Sismologie Solaire) and BISON (Birmingham Solar Oscillations Network) which also measure global Sun velocity oscillations in the full-disc integrated light using a similar technique to GOLF (vapour resonance spectrophotometers).

Earlier comparisons of the noise model with ground-based data showed agreement to within a factor of 2 over the frequency range in which the so-called 'g-mode oscillations' (which, one hopes, will reveal the structure of the innermost part of the solar globe) are to be expected. This had been taken as confirmation of the model, as well as an indication that the Earth's atmospheric disturbances do not make a significant contribution to the observed data.

Now, for the first time, the frequency spectrum of surface velocity has been measured from space and these observations from SOHO have completely changed the picture. Figure 2 shows the Harvey model noise spectrum plotted together with preliminary results from GOLF and from Mark-I, a ground-based instrument in the BISON network at IAC Tenerife, regarded as one of the best of the ground-based observing stations. The data

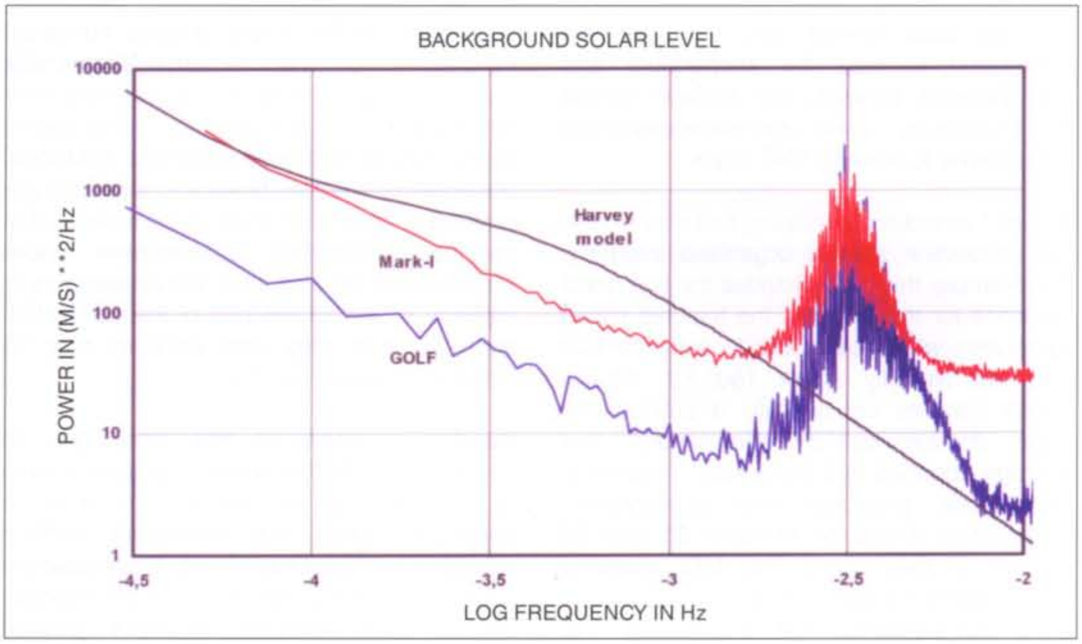


Figure 2. Comparison of the background solar-noise model (as estimated by J. Harvey in 1988) with measured velocity power spectra from GOLF on board SOHO and the ground-based Mark-I instrument. Note the significantly reduced noise in the GOLF spectrum at low frequencies.

from GOLF and Mark-I are the result of an analysis made by Pere Pallé at the Instituto de Astrofisica de Canarias (IAC). The peak at 3 MHz is caused by the 5-minute p-mode (i.e. sound-wave-driven) oscillations. At lower frequencies, the signal level from GOLF is an order of magnitude lower than from Mark-I or the model. We conclude that atmospheric disturbances account for the major part of the noise received on the ground at these frequencies, and that the model greatly overestimates the solar background level. The consequences for SOHO are very positive: the strategy of making such observations from space is fully vindicated and the detection limit for low-level oscillations or g-modes is lower than anticipated, by a factor of ten or more.

VIRGO's operation started with Sun Photometer (SPM) measurements of the spectral irradiance at 402, 500 and 862 nm and with the radiometers for total irradiance in mid-January 1996. The measurements with the Luminosity Oscillation Imager (LOI) started only at the end of March after the successful opening of its cover (which had earlier reverted to the closed position each time it was actuated with the open command!).

The power spectra calculated from the time series of the total and spectral observations are shown in Figure 3. Firstly, the 5-minute oscillations can be seen very clearly: on a widely expanded scale, the amplitudes of the individual p-modes have a signal-to-noise ratio never previously seen. In the range between 50 and 1000 μHz (0.5 – 5 h periods), which could not be observed before SOHO, the power spectra from the red and total to the blue flatten out at around 100 μHz to an increasingly stronger degree and, in the range below about 80 μHz, have equal power for all wavelengths. In the range in which the granulation is the dominant noise source, and where the p-mode oscillations are observed, the blue/green/red to total ratio is about 7:5:1 in terms of power. The g-modes are expected to be observed in the range of low solar power. Thus, what was said above in the context of the GOLF data is confirmed: the Sun seems to be quite cooperative in the search for g-modes. This is ultimately the main objective of VIRGO. At present, g-modes still seem to be hidden in the noise, but if they do indeed exist longer-duration observations will reveal them.

At very low frequencies (corresponding to periods of days and weeks), the small activity features that have passed the visible disc have been observed with all of the VIRGO instruments. An example is a very small active region which passed the central meridian in mid-May. It could be followed by the LOI passing through its four pixels north of the equator, showing an increase in intensity close to the limb, a decrease near the central meridian, and again an increase before vanishing at the west limb. The simultaneous observations with the SPM and the radiometers are now allowing temporal and spatial variations to be disentangled, which in turn will greatly improve our understanding of solar irradiance variability. Although the passage of the spot around the central meridian decreased the total radiation by only about 0.02 percent, the whole effect can be investigated in detail. This demonstrates the high signal-to-noise ratio being achieved with the Sun in the quiet part of its activity cycle, but also, and perhaps mainly, due to the very quiet environment of SOHO.

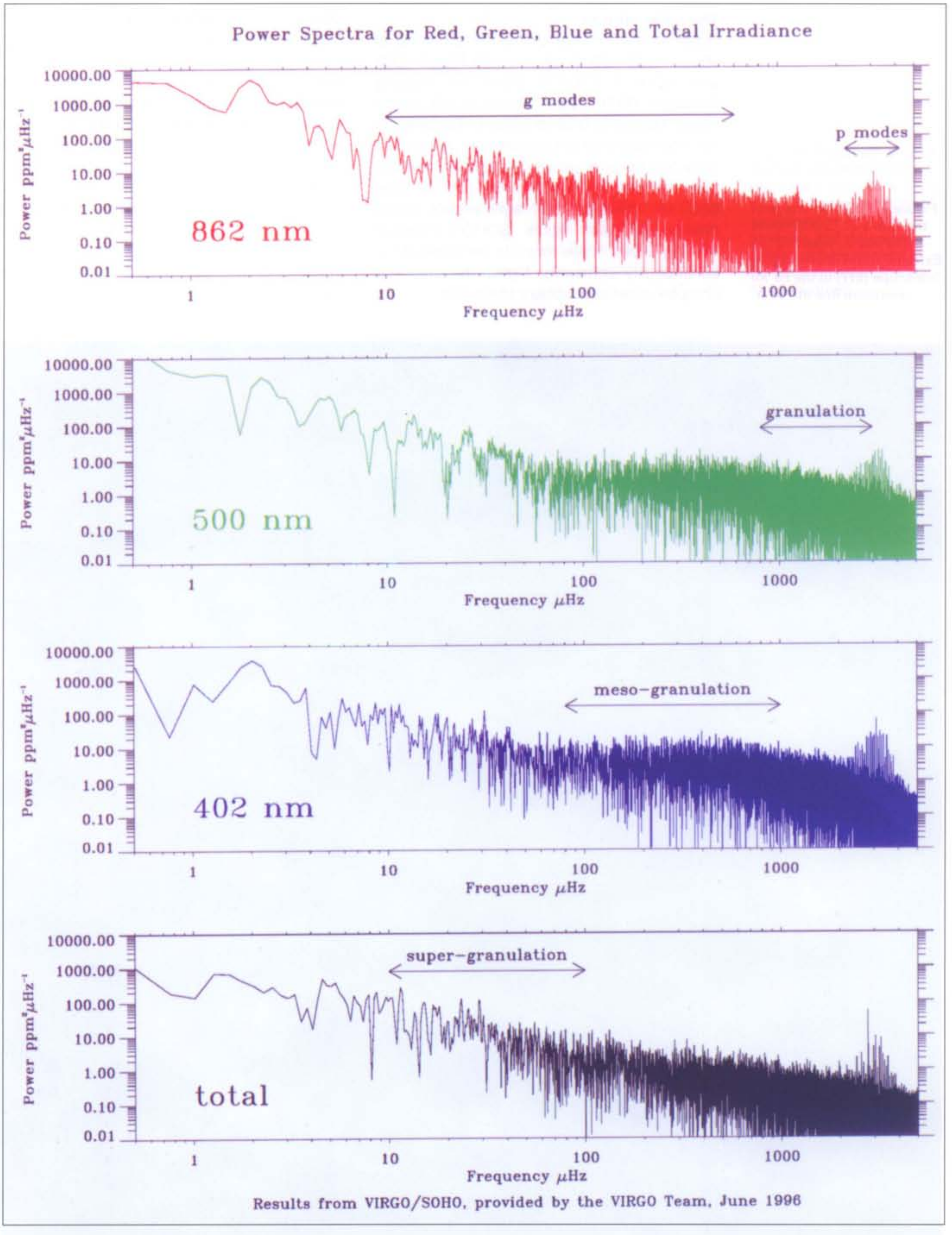


Figure 3. Power spectra from time series of total solar irradiance and of spectral irradiance at 402, 500 and 862 nm, obtained by VIRGO. The dominant noise sources, as well as the expected g-mode frequency range, are indicated.

The solar corona

Figure 4 is an image of the Sun's corona at about 1 500 000 K, taken on 13 March 1996 with SOHO's Extreme Ultraviolet Imaging Telescope (EIT). Every feature in this image traces magnetic-field structures. Because of the high quality of the instrument, we can see more subtle and detailed magnetic features than ever before. This is the first time we have been able to get such images except during five-minute rocket flights. SOHO's constant viewing allows movie loops to be made of the continuously changing, highly dynamic and complex outer atmosphere of the Sun.

'Plumes' of outward-flowing hot gas in the Sun's atmosphere may be one source of the solar wind of charged particles. Figure 5 shows (top) magnetic fields on the Sun's surface near the solar south pole; an ultraviolet image (centre) of the 1 000 000 K plumes from the same region; and an ultraviolet image (bottom) of the 'quiet' solar atmosphere closer to the surface. The topmost image was taken by SOHO's Michelson Doppler Imager/Solar Oscillations Investigation (MDI/SOI) instrument. The centre and bottom images were taken by EIT.

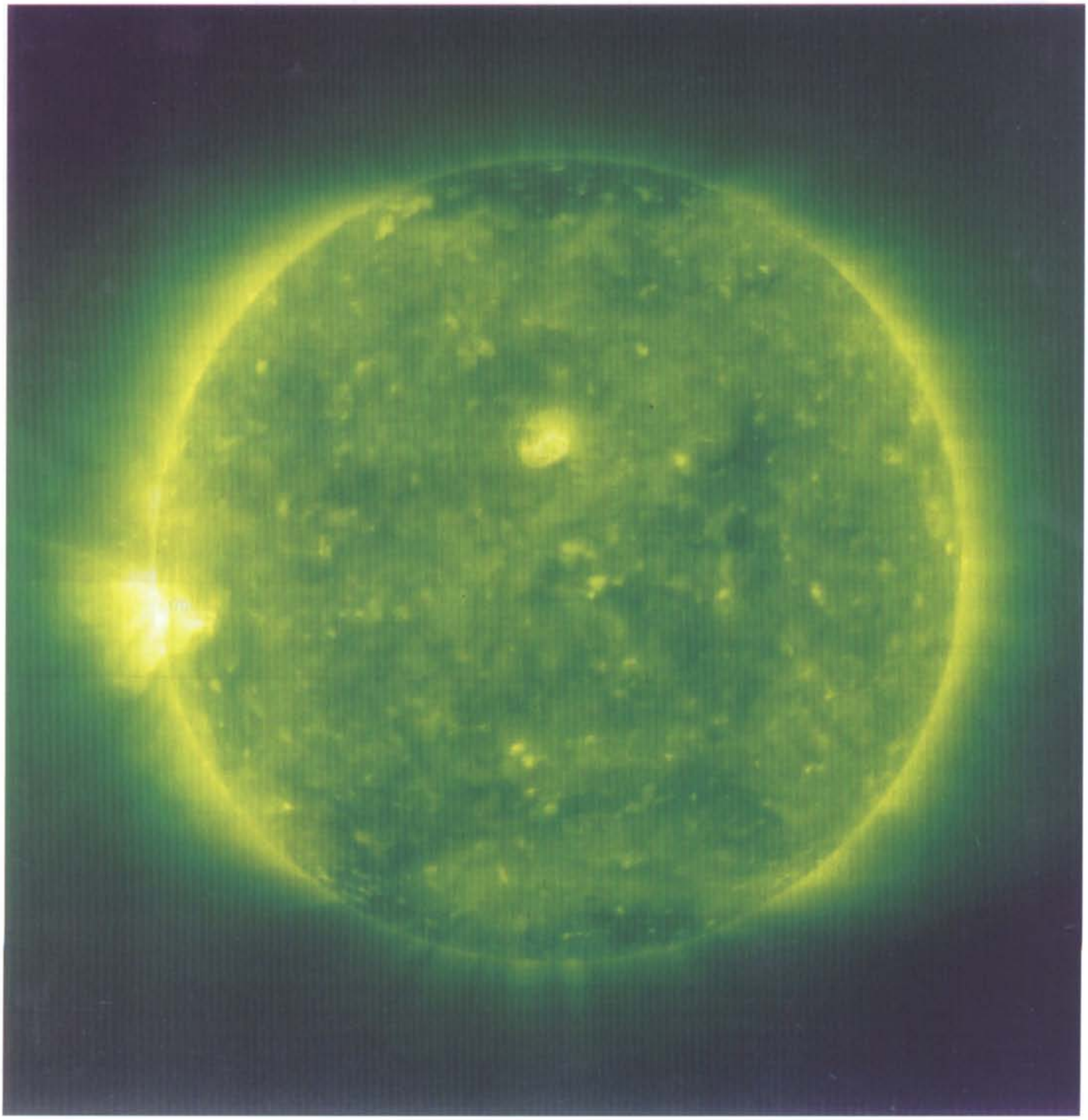


Figure 4. Full-disc image of the Sun's corona at about 1 500 000 K, taken by the Extreme Ultraviolet Imaging Telescope (EIT) in the Fe XII emission line at 195 Å.

These images represent the first opportunity scientists have had to see the detailed development over time of the polar areas, with their plume structures where the solar wind is accelerated. Again, SOHO's continuous viewing of the Sun from outside the Earth's atmosphere allows movies to be made, which will help us to understand the relationship between the magnetic field and the polar plumes in the wider context of the solar polar caps.

Figure 6 shows a sequence of images of the Sun in ultraviolet light taken by EIT on 11 February 1996. An 'eruptive prominence', or blob, of 60 000 K gas, over 130 000 km long, was ejected at a speed of more than 25 000 km/h. The gaseous blob is shown to the lower right in each image. These eruptions occur when a significant amount of cool dense plasma or ionised gas escapes from the normally closed, confining, low-level magnetic fields of the Sun's atmosphere to streak out into the interplanetary medium, or heliosphere. Eruptions of this sort can produce major disruptions in the near-Earth environment, affecting communications, navigation systems and even power grids. SOHO, with its

Figure 5. The south pole of the Sun: magnetic field (top), the 1 000 000 K corona as seen in the Fe IX emission line at 171 Å (middle), and the upper chromosphere as seen in the He II emission line at 304 Å (bottom).

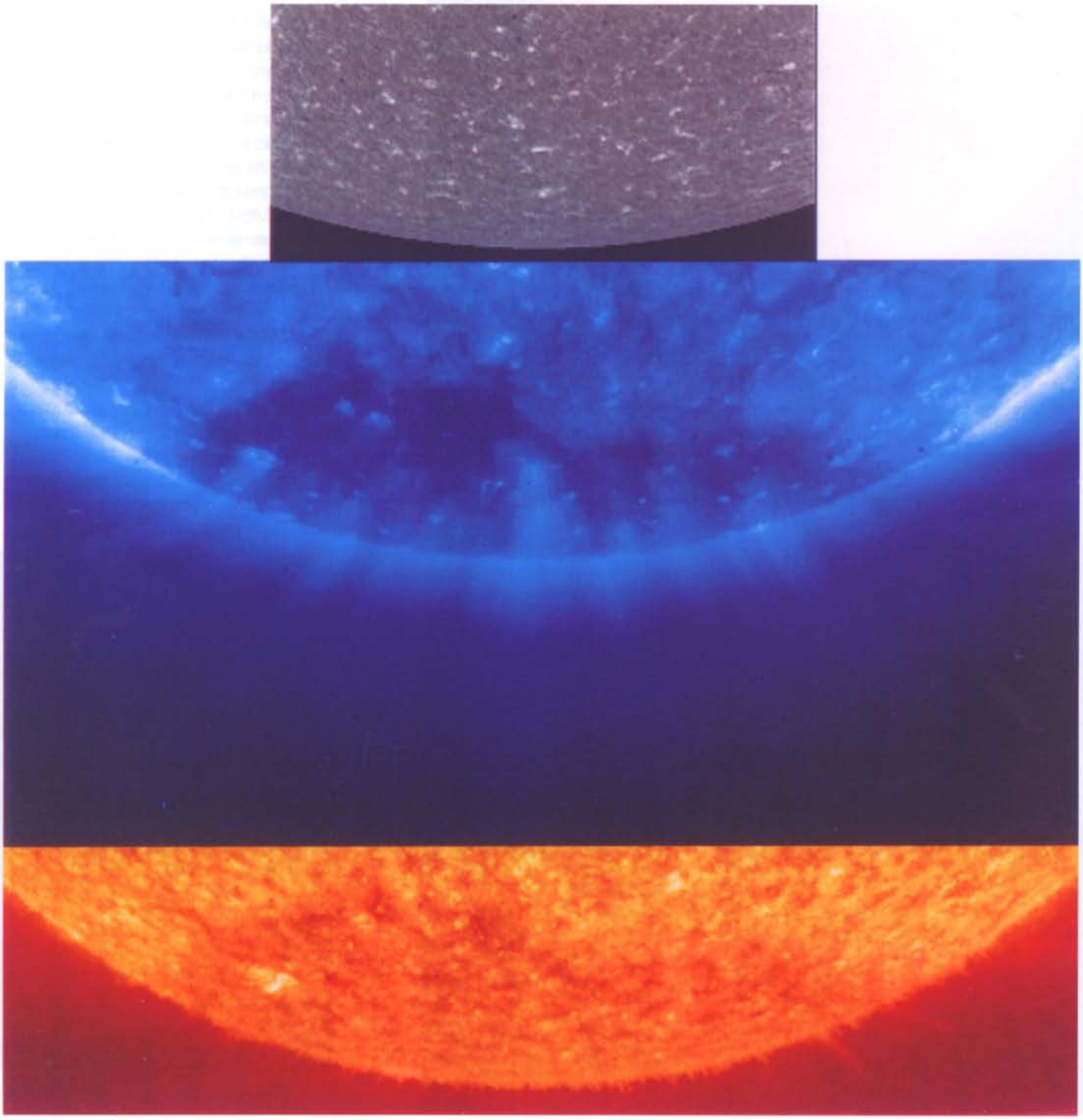
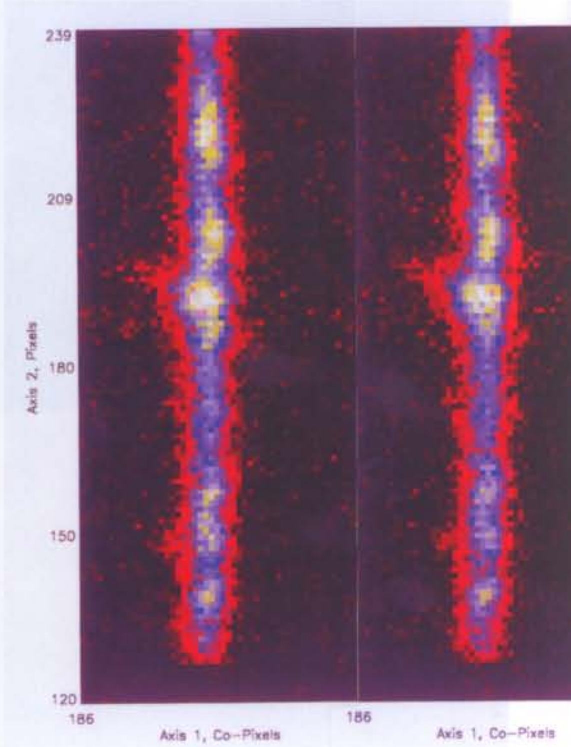


Figure 6. Eruptive prominence recorded by EIT in the He II emission line at 304 Å (images, rotated here through 90°, taken approx. 20 minutes apart)

comprehensive diagnostic instrumentation and its uninterrupted view of the Sun, can observe such events continually and is allowing us for the first time to acquire a better understanding of how such violent events occur.

SUMER – Solar Ultraviolet Measurements of Emitted Radiation – observed its first light on 24 January 1996, and obtained a detailed spectrum in the wavelength range from 500 to 1490 Å of a solar region near the north pole. Using the second detector of the instrument, this range was later extended to 1610 Å. Many more features and areas of the Sun have been observed since then, including coronal holes, polar plumes and active regions. Because of the technological advances employed in SUMER, we have been able to detect lines that are much fainter than previously observed. SUMER has already recorded over 2000 extreme-ultraviolet emission lines and many identifications have been made. The ions emitting this radiation persist at temperatures between 10 000 and 2 000 000 K and are thus ideally suited for investigations of the solar transition region where the increase occurs from chromospheric temperatures near 10 000 K to coronal conditions at several million Kelvin.

Among the many theoretical concepts of how the Sun heats its corona, reconnection



processes of oppositely directed magnetic field lines play a prominent role. SUMER with its high spatial, spectral and temporal resolution is allowing us to investigate small-scale reconnection events. One example, in the transition region that lies between chromosphere and corona, has been observed near the Sun's centre in the O VI line (1031.91Å), which is formed in plasma at temperatures of approximately 300 000 K.

Figure 7 shows a time series for the event in question with exposures every 6 seconds in the same format. Each spectrum strip depicts a 1 arcsec x 2 arcmin area on the Sun, corresponding to 700 x 77 000 km^2, which is about 1/100 000 th of its total surface area. The spectral range shown is 1.7 Å and the pronounced protrusions of the spectral-line images to shorter wavelengths, which developed with time, stems from Doppler-shifted radiation indicating a bulk velocity of the emitting ions of up to 120 km/s towards SOHO, which is superimposed on their thermal and turbulent velocities. The north – south dimension of the event (along the slit) is more than 5000 km. As the axis of the protrusion is inclined with respect to the dispersion direction, it appears as if, in this particular case, the velocity vectors of the ions were at an angle to the line-of-sight. The distance of the apparent motion along the slit would be of the order of 4000 km. The growth phase for this event lasted about 30 s, which is quite typical and, consequently, a true (as opposed to projected) velocity of 130 km/s was deduced.

The Coronal Diagnostic Spectrometer (CDS) on board SOHO is a twin extreme-ultraviolet spectrometer that looks at the Sun in the wavelength range 150 – 780 Å. The Normal Incidence Spectrometer (NIS) provides stigmatic spectral images in two wavelength bands. The Grazing-Incidence Spectrometer (GIS) has a more complete and extended spectral coverage, particularly including the wavelength range 150 – 220 Å, which is particularly well-suited for plasma temperature and density diagnostics, yet has only been little explored so far. CDS is therefore being used to determine detailed properties of the solar atmosphere in order to understand its heating and other dynamic processes.

The CDS wavelength range covers lines and continua emitted from the chromosphere at temperatures of approximately 20 000 K, to the hottest parts of active coronal loops at several million degrees. A large number of lines from a dozen chemical elements in several stages of ionisation are apparent. This allows simultaneous measurements of temperatures, densities, flows and elemental abundances within individual solar structures in the quiet Sun, coronal holes and active regions. By rastering the instrument slit, the spectrometer also builds up quasi-monochromatic images of solar features in a number of spectral lines. Each image contains detailed spectral information about the line and its immediate vicinity, and thus can be used to produce maps of total emission, velocities, plasma densities and

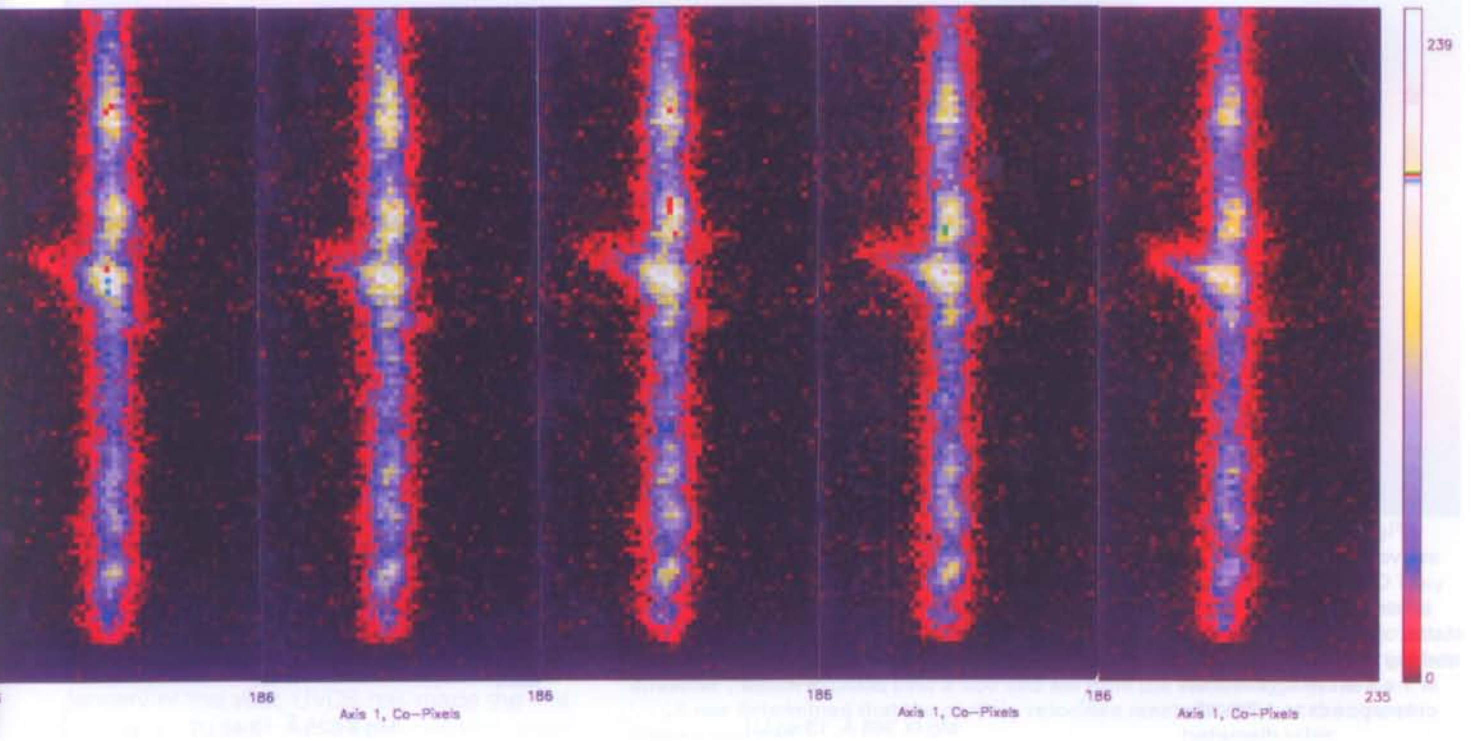


Figure 7. Temporal development of an explosive event as recorded by SUMER in the O VI line at 1031.91Å. An exposure was taken every 6 s.

temperatures over a wide temperature range.

By use of its normal- and grazing-incidence spectrometers, CDS has recorded spectral atlases for a variety of features: active regions, quiet Sun and coronal holes. These spectra represent a great improvement over earlier spectral mapping of the solar emission, particularly at the short end of the CDS spectral range. The reason for this is the combination of good angular and spectral resolutions, with a CDS spatial element size of 2 arcsec the spectral element in the range 0.07 – 0.2 Å, depending on the spectrometer type and spectral range. Thus, the short-wavelength region below 220 Å with many strong lines from different ionisation stages of iron, from Fe IX to Fe XIV, have provided good temperature information in a typical coronal plasma at 1 to 2 million Kelvin. A comparison of these spectra taken for different targets shows strong emission from Fe XIV lines in an active region. These lines become weaker in a quiet-Sun area, while the lower ionisation stages (Fe IX), representative of cooler plasma, completely dominate in the coronal hole. The evolution and structure of coronal holes, and their role in supplying the fast component of the solar wind, are currently being studied.

Images of an active region, recorded by the Normal Incidence Spectrometer (NIS) for two wavelengths and at different times on 22 March 1996, are displayed in Figure 8. It is clear that the emitting plasma is confined in magnetic loops. The two panels across the top of the image show the active region as observed in two ionisation states of magnesium, Mg IX and Mg X, emitting at temperatures only approximately 150 000 K apart around 1 000 000 K. The detailed loop structures are different and CDS is able to distinguish these differences on a much finer temperature scale than, for example, is possible from X-ray images taken by the Yohkoh satellite. The lower two panels show images from the same ions taken approximately one hour later: considerable evolution of the structures has taken place.

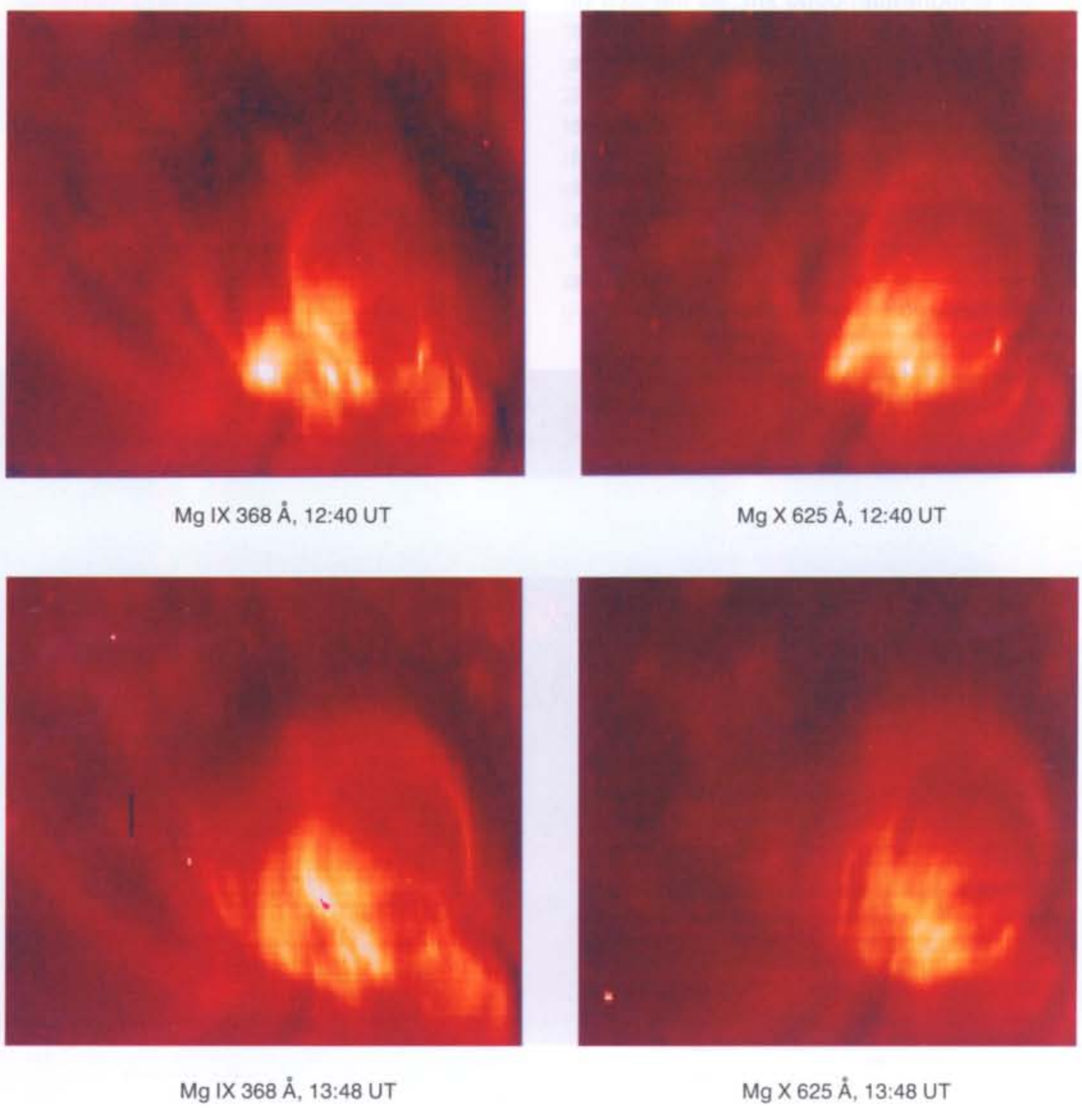


Figure 8. Images of an active region recorded by CDS with a one-hour interval in two ionisation states of magnesium, Mg IX and Mg X. The field-of-view is 4 x 4 arcmin^2 (4 arcmin corresponds to 1/8th of a solar diameter)

Analysis of line profiles recorded with the NIS has shown the presence of significant plasma flows in active-region loops. Up-flowing plasma reaching velocities of 100 km/s is seen in hot coronal lines like Fe XVI (335 Å). Other observations of an active region show down-flowing material with a velocity of 50 km/s. Similar flows are observed in lines emitted at transition-region temperatures, demonstrating that the transition region and corona are very dynamic in nature. From the present preliminary measurements it seems possible that CDS/NIS can measure relative line shifts corresponding to velocity differences as low as 20 km/s.

CDS has also observed its first strong high-velocity event (see upper panel of Fig. 8). This event, located in the leg of an active-region loop, was characterised by extremely wide emission lines corresponding to a velocity dispersion of approximately 300 – 450 km/s. The spatial extent is small, less than 4 arcsec. The event occurred in all lines from He I to Fe XVI, i.e. over a temperature range from 20 000 to 2 500 000 K. This is a new result which has not previously been reported. The fact that such events extend simultaneously over a wide temperature range is a challenge to theoretical models, and may cause a re-examination of the contribution from explosive events to coronal heating.

SOHO's Ultraviolet Coronagraph Spectrometer (UVCS) uses ultraviolet spectroscopy to obtain an empirical description of regions in the Sun's extended atmosphere, or corona, where the primary solar-wind acceleration takes place. This information is being used to address a broad range of scientific questions regarding the nature of the extended solar corona and the acceleration of the solar wind. UVCS has observed helmet streamers (Fig. 9), which are believed to be a source of normal-speed solar wind, and it has observed coronal holes, which are the known source of high-speed solar-wind streams. An understanding of the physical processes that control solar-wind acceleration will also contribute to our understanding of mass loss in other stars.

Since the start of its observations in late January of this year, UVCS has made the first ultraviolet images of the extended solar corona above two solar radii from the centre of the Sun. It has sensed the presence of a broad range of chemical elements in the extended corona, and it has actually measured the speed of coronal material as it is accelerated away from the Sun. UVCS has confirmed that protons and the more massive oxygen particles are hotter than the electrons in the outflowing coronal gas. This temperature difference may be the key to identifying the physical processes responsible for solar-wind acceleration and for controlling the composition and temperatures of solar-wind particles near the Earth. UVCS has made the first measurements of the speed of highly charged oxygen as it flows out of the tips of streamers (Fig. 9b) and has also made the first measurements of the supersonic

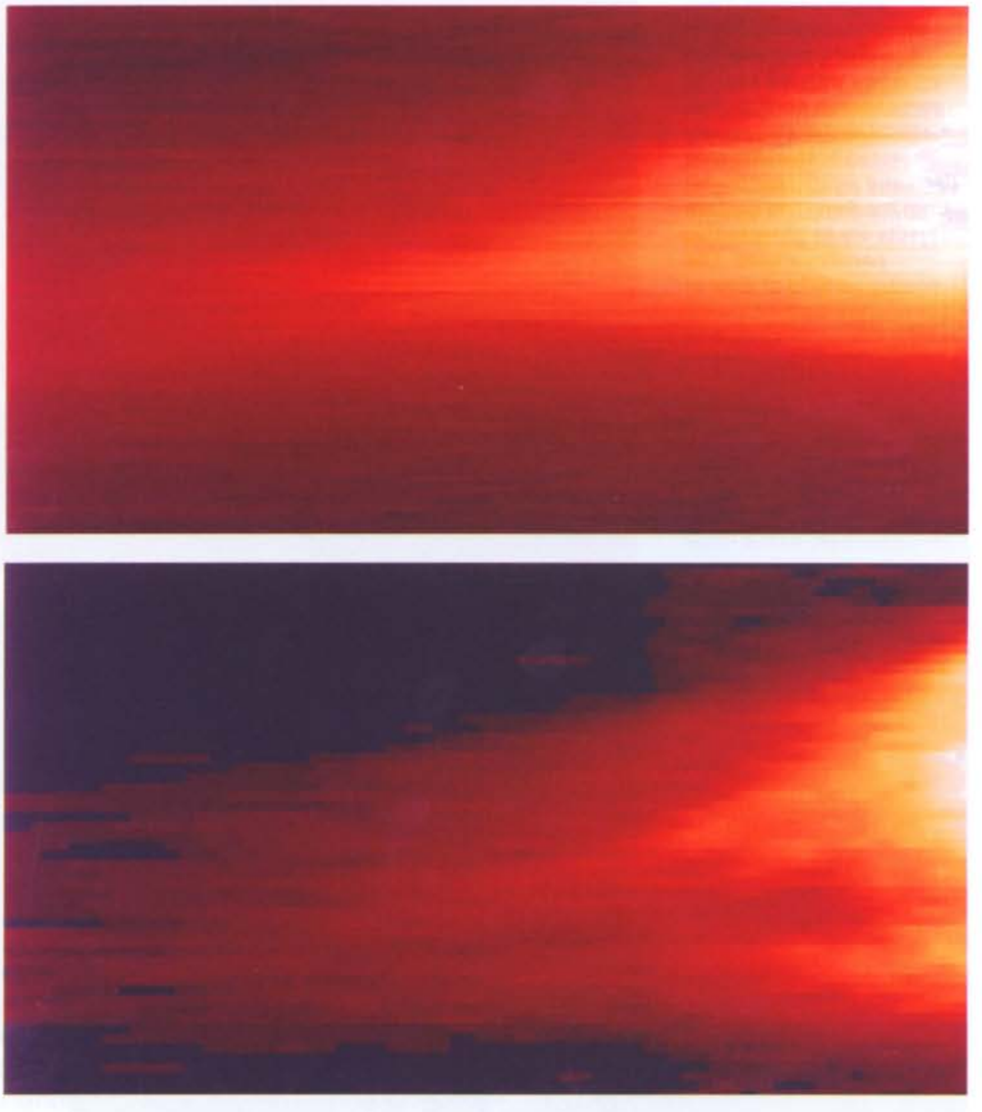


Figure 9. These images obtained by SOHO's Ultraviolet Coronagraph Spectrometer (UVCS) are the first of the extended corona in the ultraviolet. They are of atomic hydrogen (a) and highly charged oxygen (b), which flow out of the Sun along with other atomic particles to form the normal-speed solar wind. This material is shaped by the Sun's magnetic field into a giant nozzle called a 'helmet streamer', which extends over 3 000 000 km from the visible edge of the Sun. UVCS has determined that the particle velocities reach 100 km/s at the tips of these structures.

outflow of highly charged oxygen from coronal holes. This information is being used to test theoretical explanations of how the solar wind is accelerated.

LASCO uses three coronagraphs to observe the outer solar atmosphere from near the solar limb to a distance of 21 000 000 km (i.e. about one seventh of the distance between the Sun and the Earth). Coronagraphs, which are special telescopes that can image the faint corona in the presence of the glaring light of the visible solar disc, can also observe the innermost corona from the ground. The extreme reach of LASCO can, however, only be achieved from space because of the scattering of sunlight in the Earth's atmosphere.

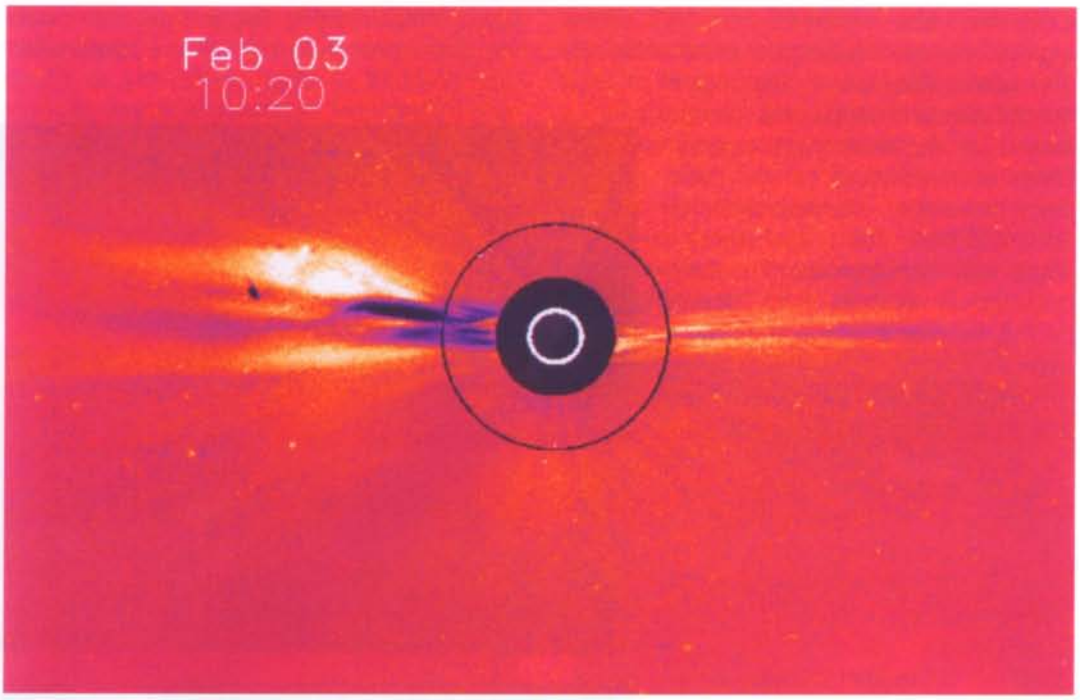


Figure 10. Global coronal disturbances as seen by the LASCO C2 and C3 coronagraphs: instead of a single coronal mass ejection erupting in one direction, movies made with the LASCO coronagraph confirm that material is simultaneously ejected both eastwards (left) and westwards (right) from the Sun. The eastern ejecta are brighter in this particular case. The combined field of view of the images spans 25 solar radii. The inner edge is at 1.6 solar radii. The dark circle marks the boundary between the C2 and C3 fields of view. Bright areas are coronal clouds moving outwards. Dark areas resemble the blown-out streamer belt. At the inner edge (420 000 km above the solar surface), velocities are typically 90 km/s; at 23 solar radii (15.7 million km above surface), they are 530 km/s.

Coronal Mass Ejections (CMEs) are huge clouds of coronal plasma (10^{12} – 10^{13} kg) ejected from the Sun at extremely high speeds (from several hundred to 2000 km/s). After acceleration at the Sun, they travel through interplanetary space and reach Earth in 2.5 to 5 days. When they reach the Earth, CMEs cause disturbances in the magnetosphere, which trigger auroras, make magnetic navigation at high latitudes difficult, and sometimes cause current spikes in high-voltage power lines, resulting in power outages and occasionally in the destruction of power equipment. They can also damage or destroy Earth-orbiting satellites.

Figure 10 shows a frame of a large CME as observed by the outer two LASCO coronagraphs (C-2 and C-3) on 3 February 1996. This event, because it was seen in the field of view of these two coronagraphs, could be followed from 1 100 000 km above the solar surface out to 15 000 000 km. Bright clouds are seen travelling outward in the equatorial plane with speeds ranging from 90 to 540 km/s, over both the east and west limbs of the Sun. The acceleration takes place over a distance of 15 000 000 km. The sectors above the solar limb in which the bright clouds are seen seem to extend over an angle of 120 deg in the equatorial plane. Although the instruments cannot see material moving towards or away from the Earth – Sun line, it is safe to assume that the CME extended all the way around the Sun. A faint event above the Sun's south pole is also apparent in this picture.

A thin magnetic current sheet forms around the Sun during a minimum in the solar cycle. The acceleration of the global coronal disturbances seems to occur in this sheet. The upper and lower boundary layers of this sheet have opposite magnetic polarities. Consequently, the two boundary layers attract and form a 'lid', thereby trapping hot coronal material in the corona's outer layers. The amount of material stored varies greatly with time. The upper panel of Figure 11 shows the current sheet during a quiet period, the lower panel the same area two days prior to the 3 February CME. The obvious increase in brightness prior to the CME indicates that more material is stored before a global coronal disturbance than during quiet coronal periods. It is assumed that the current sheet will blow open when the pressure inside exceeds a

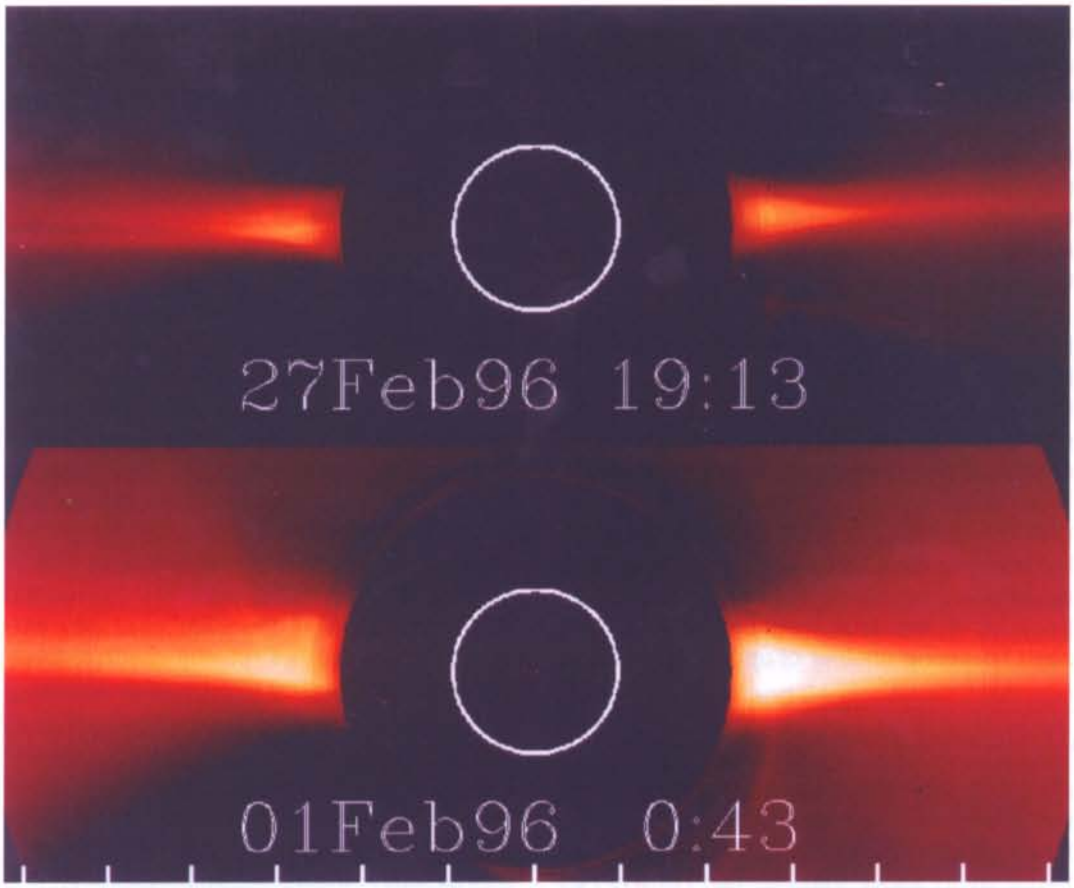


Figure 11. Streamer belt seen in the field of view of the LASCO C2 coronagraph. Upper panel: during a quiet period. Lower panel: during an active period prior to a coronal mass ejection. The field of view covers 1.6 to 6 solar radii (420 000 km above the solar limb to 3.6 million km).

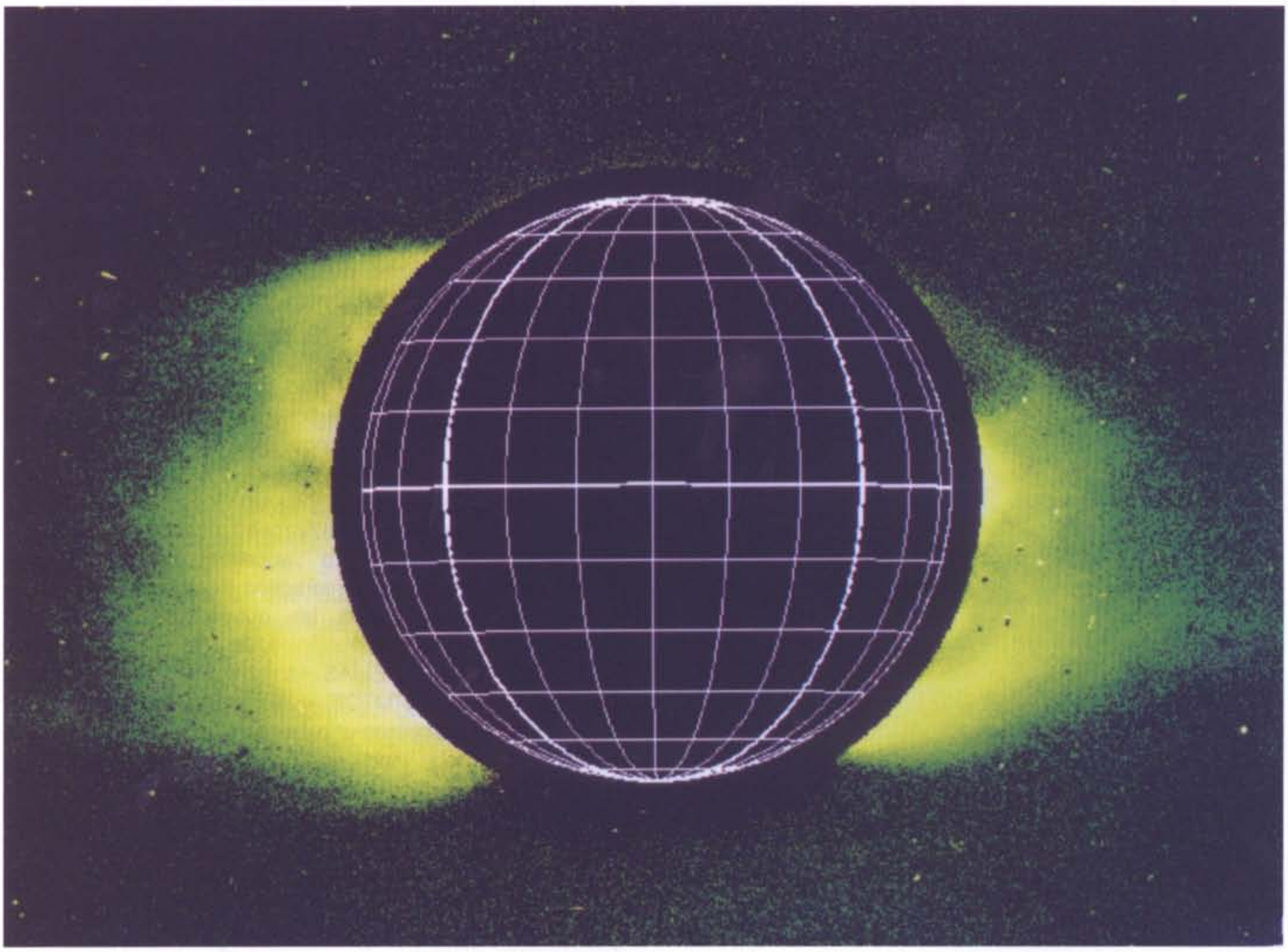


Figure 12. The inner corona as seen by the LASCO C1 coronagraph in the light of the green forbidden coronal line of Fe XIV. Coronal structures can be seen as high as 1 000 000 km above the solar surface.

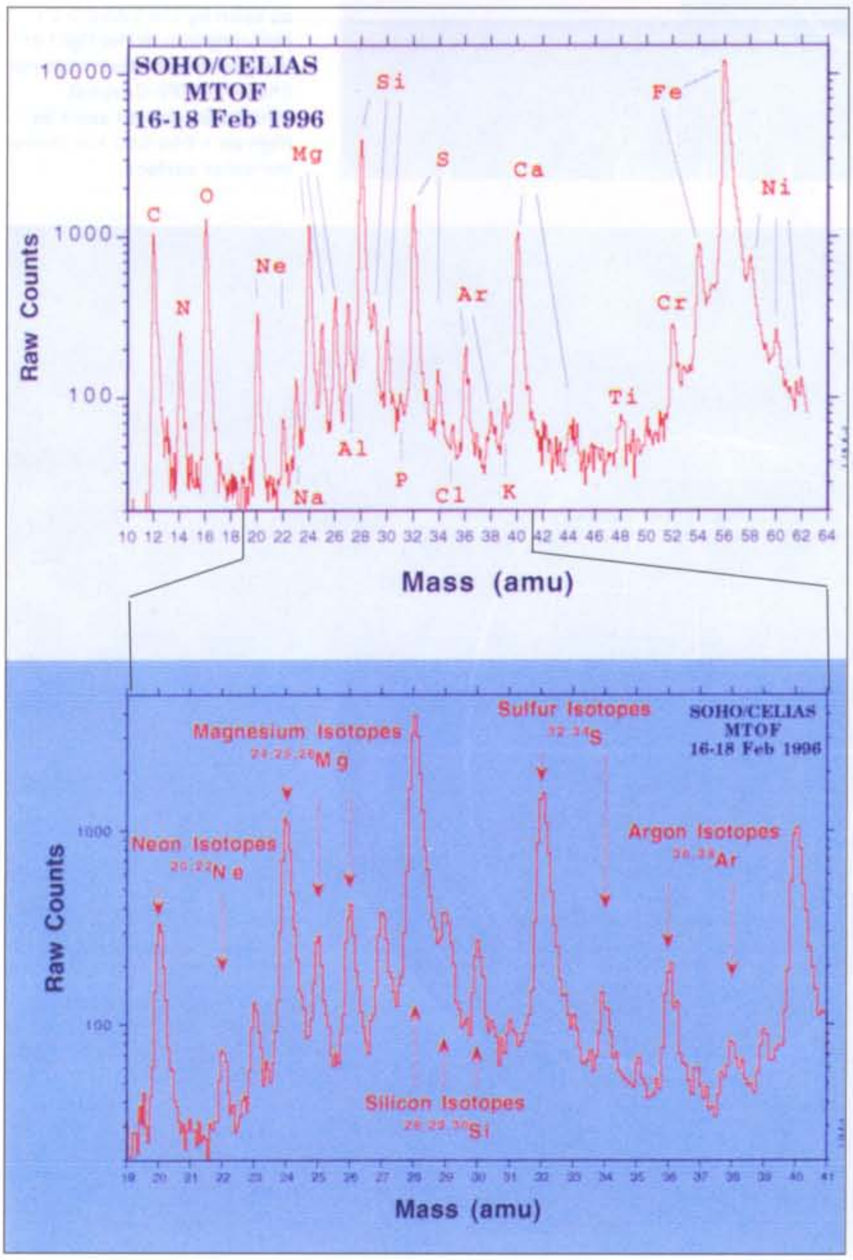


Figure 13. Element and isotope spectrum as obtained with the MTOF sensor of the CELIAS experiment. Many elements such as phosphorus, chlorine, potassium, titanium, chromium and nickel are being measured in the solar wind for the first time.

certain value. An instability will then accelerate and release the stored hot coronal material as a global coronal disturbance.

Figure 12 shows the inner corona as seen by the innermost LASCO coronagraph, C-1, in the light of the green, so-called 'forbidden' (i.e. inherently very weak) coronal line of Fe XIV. Coronal structures can be seen as high as 1 000 000 km above the solar surface. The large-scale solar magnetic field is being traced by loop systems, which are forming all around the Sun in different latitude zones, as demonstrated by the appearance of the corona above both the east and west limbs. Three loop systems can be seen from high northern to high southern latitudes, bridging the solar equator. This magnetic configuration is known as a 'magnetic quadrupole', because it has four magnetic zones, each zone bordering another of opposite polarity in an inherently unstable configuration. This picture was taken two days before the coronal mass ejection shown in Figure 10 was observed.

Solar wind

The solar wind is a hot gas of electrically charged atomic particles that streams out of the Sun at hundreds of kilometres per second and fills the surrounding space, i.e. the heliosphere, and is therefore also present throughout the Solar System. The solar wind causes the aurorae that occur sporadically at middle and high latitudes over both hemispheres of the Earth in the form of luminous bands, it causes comets to have tails, and it sometimes induces changes in the Earth's magnetic fields that can also disrupt communications and cause power-grid failures. Changes in the solar wind may also affect the properties of the Earth's lower atmosphere, including weather and climate.

The Charge, Element and Isotope Analysis System (CELIAS) investigation on SOHO is a multi-sensor experiment consisting of three detectors that measure the composition and energy spectra of plasma (solar wind) and energetic ions of solar, interplanetary, and interstellar origin. A fourth sensor monitors the absolute EUV (extreme ultraviolet) flux from the Sun. The in-situ particle measurements, when combined with optical coronal measurements and modelling efforts, yield information on the processes by which matter from the underlying solar atmosphere is fed into the solar corona. These processes lead to enrichments/depletions and other variations in elemental abundances, ionic charges and isotopic heavy-ion abundances in the corona and solar wind and solar energetic particle events which, in turn, provide clues as to the acceleration and heating mechanisms of solar-wind particles in the inner corona, as well as the temperature and density gradients in the latter. Other studies include the dynamics of pick-up ions (involving both particle and EUV measurements), and particle sources and acceleration in so-called 'Corotating Interaction Regions' (CIRs), which are located far out in the heliosphere.

The CELIAS solar-wind mass spectrometer (MTOF = Mass Time-of-Flight sensor) possesses unprecedented mass resolution for solar-wind composition studies, and has already measured rare elements and isotopes that were previously not resolvable from more abundant neighbouring species, or were not previously observable at all. For example, as can be seen in Figure 13, the elements of sulphur, argon and calcium are now easily distinguished from their neighbouring species silicon and iron, as is nitrogen from carbon and oxygen. The rare elements phosphorus, chlorine, potassium, titanium, chromium and nickel are being measured in the solar wind for the first time.

The determination of the elemental abundances of these rarer species allows us to fill in the 'blanks' in the tables comparing the abundances in the solar wind with those in the photosphere, i.e. on the solar surface. This is important for better analysis of the processes that feed and accelerate the solar wind in the chromosphere and inner corona. The solar-wind and coronal abundances indicate an ordering of relative abundance enhancement (or depletion) to photospheric values partially correlated with the First Ionisation Potential (FIP) of the element – the so-called 'FIP effect'. Since these newly observed elements have different properties (such as first ionisation potentials and times, charge-state equilibrium times, atomic mass, etc.), knowledge of their relative abundances serves as a further diagnostic tool. They help in determining conditions in the chromosphere/transition region, where ions which eventually become the solar wind are separated from neutrals.

The FIP effect is not the same for all types of solar wind. The temporal resolution of CELIAS means that abundance variations in different types of solar wind (e.g. coronal-hole-associated versus slow solar wind) may be better traced to the varying conditions in the solar-wind source regions.

The MTOF sensor – the first of its kind to be mounted on a Sun-pointing (rather than spinning) spacecraft – is routinely measuring isotopic abundance variations for several elements (neon, magnesium, silicon, sulphur, argon, calcium, iron and nickel), some of which have not previously been observed either in the solar wind, in solar energetic particles, or spectroscopically. Isotopes are also being measured with a much finer temporal resolution than previously available (of the order of minutes/hours instead of months/years).

Matter in the corona and solar wind is derived from the Outer Convective Zone (OCZ) of the Sun and isotopic abundances of the less volatile elements in the solar atmosphere are probably very similar to terrestrial, lunar and meteoritic abundances. For such elements, it is possible to infer the amount of isotopic fractionation under varying conditions in the solar-wind source region. For many species, the solar wind provides the only source of information on the isotopic composition of the OCZ. This is important for many cosmochemical and astrophysical applications: knowledge about the OCZ's isotopic composition will yield information on the early solar nebula and the history of the Solar System.

The COSTEP instruments measure electrons from 45 keV to 10 MeV and hydrogen and helium nuclei from 45 keV to 53 MeV. Given the current phase in the solar-activity cycle, which is close to solar minimum, the Sun was extremely quiet during the first phase of the mission. Figure 14 shows, from the top, counting rates for electrons (200 – 700 keV, EPHIN), protons (80 – 150 keV, LION), protons (4.3 – 7.8 MeV, EPHIN) and nuclei (53 MeV/n, EPHIN) from switch-on until 25 April 1996. Only three small solar events were observed, on 11 and 24 December 1995 and on 22 April 1996.

In addition to upstream events when SOHO is connected via interplanetary field lines to the Earth's bow shock (seen in the second panel of Fig. 14), two different types of recurrent events are being observed by COSTEP:

- Co-rotating Interaction Regions (CIRs), which are formed when high-speed solar-wind streams interact with the slower solar wind ahead, can accelerate nuclei up to a few MeV (panel 2 of Fig. 14) and at the same time decrease galactic nuclei (panel 4). Periods of recurrent high-speed solar-wind streams are shaded in the figure.
- Jovian electrons can reach interplanery magnetic field lines connecting to SOHO at time intervals of about 25.5 days. The upper panel of Figure 14 shows these very pronounced electron increases, which do not coincide with the nucleon increases or decreases due to CIR effects.

Of the solar-wind particle detectors on SOHO, ERNE covers the highest energies, from roughly 1 to 500 MeV/n. At these energies, the present solar-activity minimum enables ERNE to collect particles originating outside our Solar System, namely the galactic cosmic radiation. During the next five years, solar activity will increase and, accordingly, the particles collected will increasingly be of solar origin, coming from the flares and coronal mass ejections, for which the instrument was designed.

Since the activation of ERNE on 15 December 1995, only one small particle event of solar

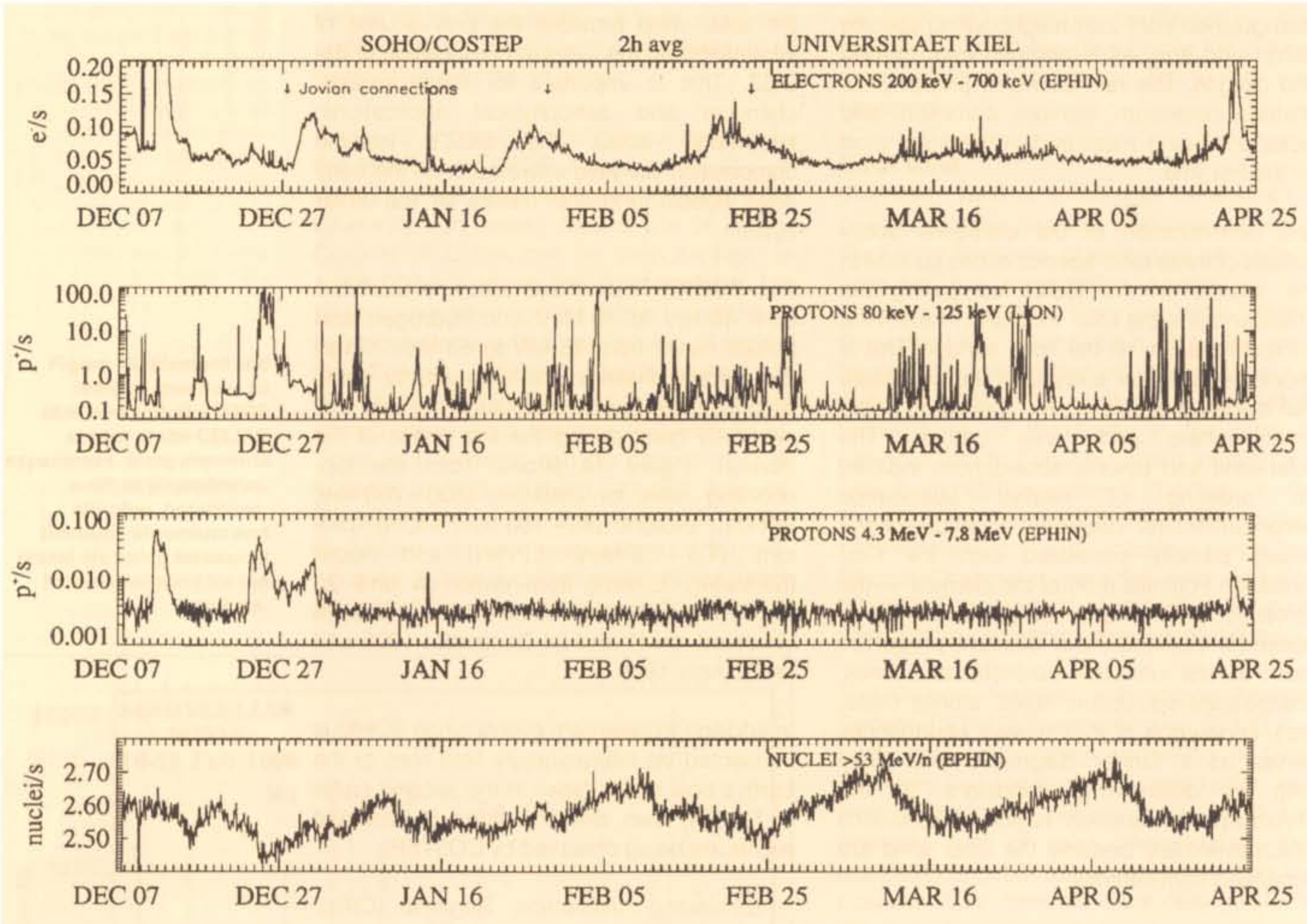


Figure 14. Count rates of electrons, protons and nuclei as measured by COSTEP.

origin has been detected, lasting from 20 to 25 January 1996. During this event, the number of protons counted rose about tenfold over the background. Initial analysis indicates that the high-energy protons detected originated in the shock front arising from a fast solar wind running into a slower part of the wind, with the collision region located several Sun – Earth radii in the heliosphere. The ERNE LED (Low-Energy Detector) is particularly well suited for the detection of such particles. Other possible solar acceleration mechanisms include the strong electric fields present in solar eruptions (impulsive acceleration, lasting perhaps an hour), and solar coronal mass ejections driving shock fronts that accelerate particles continuously as the shock approaches and passes Earth (lasting several days).

The galactic cosmic radiation that is currently observed consists of particles originating in the Milky Way, including atomic nuclei heavier than helium possibly coming from super-novae. Due to transport effects, the galactic cosmic rays are characterised by their rising spectrum. For this radiation, the ERNE HED (High-Energy Detector) has succeeded in identifying significant amounts of hydrogen, helium, boron, carbon, nitrogen, oxygen, neon, magnesium, silicon and iron.

An example of composition and energy resolution is shown in Figure 15. The two horizontal axes describe energy deposited by the incoming particle in two detector layers. The vertical axis gives the observed count rate. Carbon (the highest peak), nitrogen and oxygen are seen in this picture. To the right of the carbon ridge, some boron can be found, as well as some neon to the left of oxygen. In addition, anomalous cosmic-ray components (i.e. fake cosmic rays originating within the heliosphere) have been measured with ERNE LED for at least helium, nitrogen and oxygen.

One instrument on board SOHO avoids looking at the Sun because it would be dazzled. Instead, SWAN surveys the sky all around and sees an ultraviolet glow from (neutral) hydrogen atoms lit by the Sun (Fig. 16). These atoms come on a breeze from the stars that blows through the Solar System. However, the competing wind of charged particles from the Sun breaks up (ionises) the incoming atoms so that they can no longer emit at their characteristic wavelength. The result is a hole in the pattern of emissions

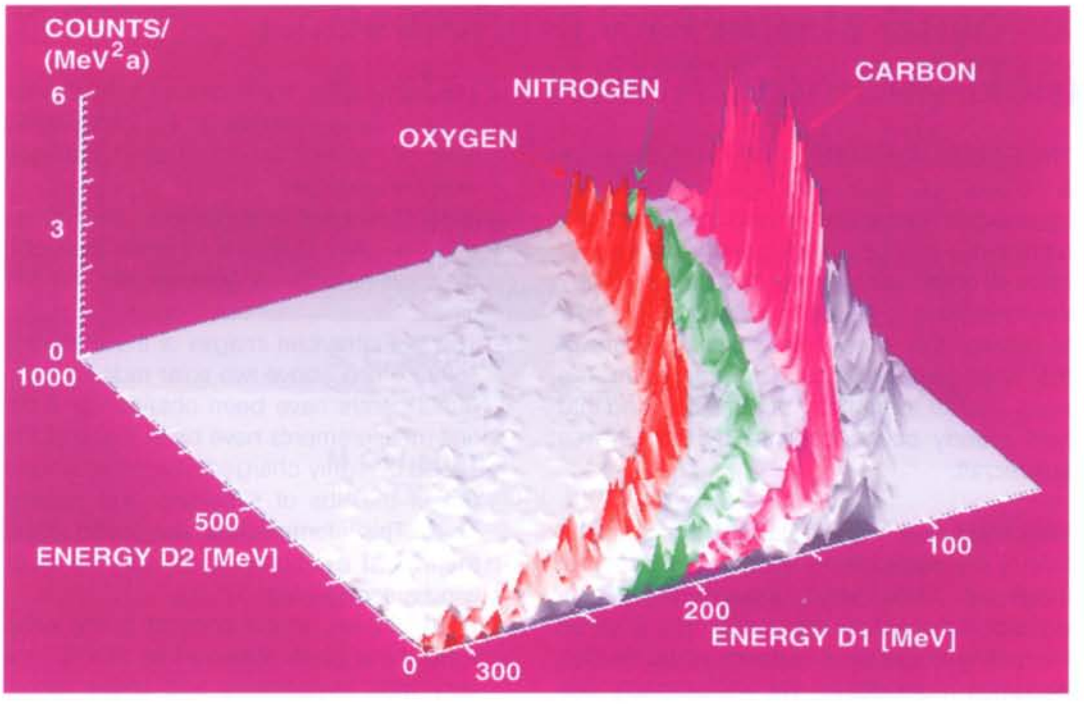
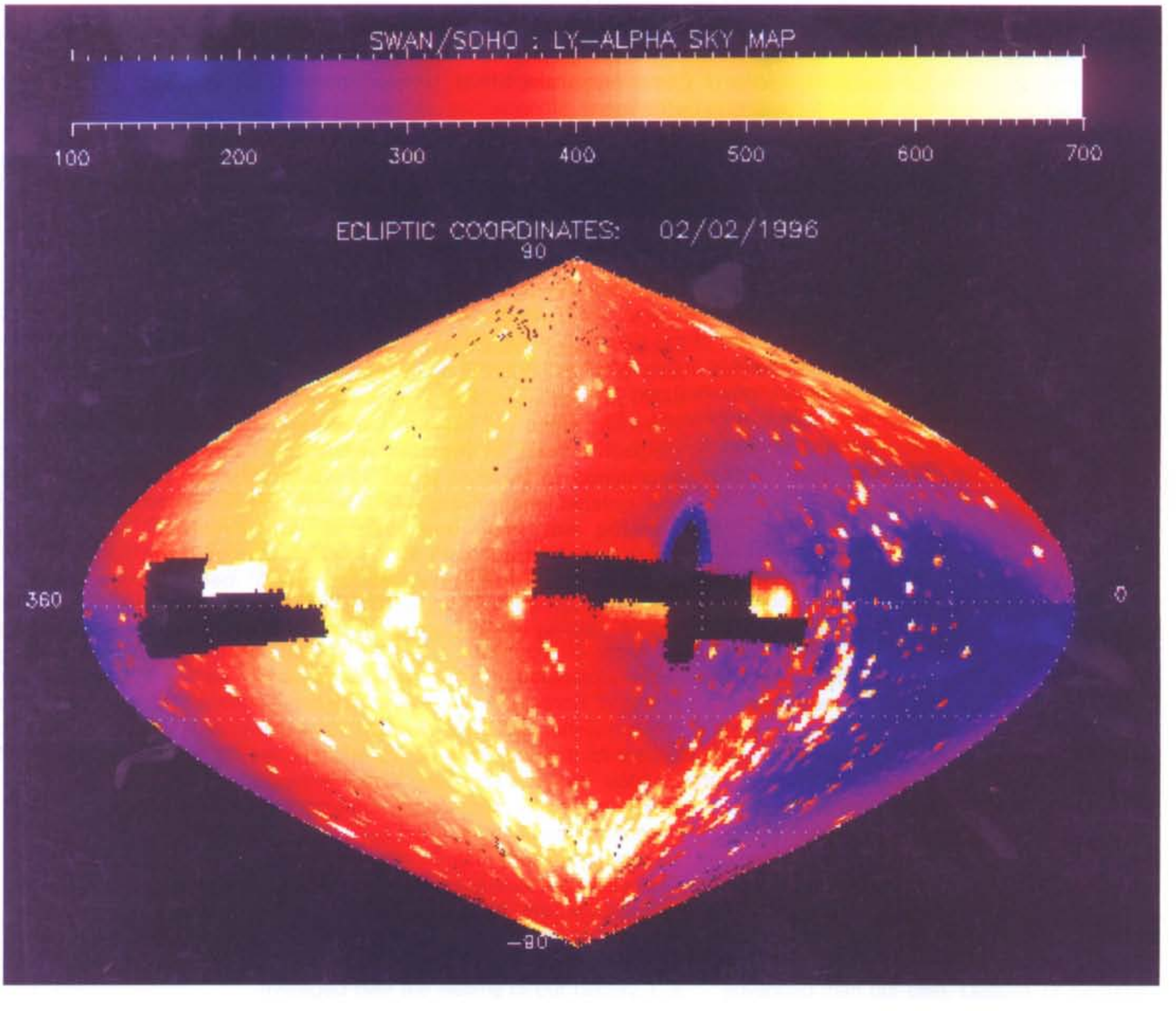


Figure 15. Composition of the galactic cosmic radiation as measured by ERNE. One can clearly identify carbon, nitrogen and oxygen. Closer inspection of the data has helped to identify other elements such as hydrogen, helium, boron, neon, magnesium, silicon and iron.

Figure 16. Full-sky Lyman-alpha map in ecliptic coordinates as recorded by the SWAN instrument. Note the asymmetry between the northern and southern hemispheres, which has also been detected by Ulysses. The U-shaped yellow band is the Milky Way.



downstream from the Sun. This allows us to determine the strength of the solar wind in different directions.

The Earth is also visible in the maps, because a cloud of hydrogen gas called the 'geocorona' envelops it and glows in the ultraviolet. In fact, the goecorona would hamper observations of the interstellar glow by satellites close to the Earth. SOHO is thus able to monitor the three-dimensional structure of the solar wind. It has also confirmed the north – south asymmetry of the solar wind that had already been observed by the Ulysses spacecraft.

With the present quiet state of the Sun, the SWAN sky maps clearly indicate a situation of increased solar wind around the Sun's equator in the ecliptic plane (Fig. 16). It will be interesting to see what happens when the Sun becomes more active. We will probably see important changes in the solar wind's impact on the interstellar gas revealed by changes in the sky maps. Meanwhile, SWAN uses alternate days for special investigations, such as observations of Comet Hyakutake which has recently swung-by the Sun.

Conclusion

During the first couple of months, after the commissioning of both the spacecraft and its experiments, all of the instruments have performed observations and measurements that demonstrate that SOHO is fully qualified to achieve the goals for which it was designed. In-depth analysis of the data is just starting, but quick analyses of the early measurements have already provided new observations in all the fields addressed by the SOHO instruments. The following are of particular relevance:

In the field of helioseismology:

- The power spectrum of the global Sun surface velocity variations, outside the resonant acoustic-wave peak around 5 mHz, is about an order of magnitude lower than previously computed from ground-based observations. Consequently, the expectation that the SOHO helioseismology instruments may be able to observe the so-far elusive solar gravity-waves is greatly increased.
- Flows under the photosphere, in the convection zone, are being measured for the first time. Three-dimensional maps are being produced which show the flows' influence in shaping the magnetic field observed in the photosphere.

In the solar atmosphere:

- The Sun, during the minimum in its 11-year activity cycle, maintains an unexpected level of activity when observed in the extreme-ultraviolet.
- Global coronal disturbances leading to coronal mass ejections in more than one direction have been observed for the first time.
- The first ultraviolet images of the extended solar corona above two solar radii from the Sun's centre have been obtained and the first measurements have been made of the speed of highly charged oxygen as it flows out of the tips of streamers and coronal holes. This information is being used to test theoretical explanations of how the solar wind is accelerated.
- Polar plumes, which connect to the polar wind, have been observed by SOHO in a very wide temperature and space range, together with the photospheric magnetic field.
- Coronal helmet structures are being analysed and the streamers into which they expand are being observed out to 30 solar radii.
- Coronal bright points and explosive events have been observed and are being analysed over a largely expanded temperature range with the help of multiple spectral measurements.
- Thousands of spectra have been observed, allowing us to measure temperature, density and bulk-flow as well as turbulent velocities throughout the solar atmosphere.

In the solar wind:

- Many elements and many isotopes have been observed for the first time. The correlative analysis of the in-situ solar-wind measurements and the remote-sensing of the corona will help us to understand the particle acceleration and the processes leading to abundance variations in the solar atmosphere.
- The shape of the interstellar neutral-hydrogen cavity carved out by the solar wind is being observed. Its evolution during the solar cycle will tell us about the changing three-dimensional distribution of the solar wind around the Sun.

Searching for Planets Beyond Our Solar System: How Astrometry Helps*

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The detection of the first extra-solar planets, using ground-based radial velocity searches, has recently been announced. The ESA space astrometry project, Hipparcos, has subsequently provided distances to, and upper limits on the masses of, these planetary systems. The way in which astrometric searches for planets compare with other search methods presently being pursued or considered (optical and infrared imaging, occultations, gravitational lensing, and spectroscopic measurements) is described, and the potential capabilities of the proposed Horizon 2000 Plus 'Darwin' and 'GAIA' missions are described. Darwin could detect Earth-mass planets around nearby stars, while GAIA would be able to see the effects of Jupiter-mass planets around hundreds of thousands of stars in our Galaxy, if they exist.

Introduction

The idea that planets, and possibly intelligent life, exist beyond our Solar System has stimulated popular and scientific imagination for centuries. Until last year, no planet detections had been reported – apart from Earth-mass objects discovered orbiting two distinct radio pulsars, where the formation process is considered to be very different from that of the formation of 'standard' planetary systems capable of supporting life.

There is, however, a simple equation which may be used to estimate the number of planets within our Galaxy – and by extrapolation, within the entire observable Universe – which could harbour intelligent life. Called the 'Drake Equation', after its originator Frank Drake, it is written as:

$$N = R_* \, f_p \, n_e \, f_l \, f_i \, f_c L$$

where R_* is the rate of star formation, averaged over the lifetime of our Galaxy, f_p is the fraction of stars with planetary systems, n_e is the mean number of planets per system suitable for life, f_l is the fraction of such planets in which life has originated, f_i is the fraction of such planets on which intelligent life has developed, f_c is the fraction of those developing a communication phase, and L is the mean lifetime of such technical civilisations. The terms are listed in order of decreasing estimates of their reliability. The first two are fully determined by astrophysical considerations; the remainder can only be estimated by appeal to numerous diverse disciplines including biology, organic chemistry, biochemistry, evolution, neurophysiology, anthropology, psychology, history, politics and sociology. In many ways, the factors in this equation simply underline our ignorance of this field.

Only the first term in the Drake Equation can be considered as being even approximately well-determined: there are some 10^{11} stars in our Galaxy, which is about 10 billion years old, leading very roughly to a value of R_* of order 10 stars per year. But even coarse statistical information on, say, the second and third terms is not yet available. Presently, therefore, the equation is of little practical help in assessing whether planets are common, whether the conditions necessary for life are common and, ultimately, whether life itself is common elsewhere in the Universe. We remain completely unsure whether life exists in only one place within the entire Universe – on Earth – or whether the Galaxy, and indeed the Universe, teems with civilisations far more advanced than our own. Despite, or perhaps

* Based on a lecture given at the Alpbach Summer School in July 1995

Figure 1. The final trajectory of Comet Shoemaker-Levy 9 observed by the Hubble Space Telescope on 17 May 1994, when its train of 21 icy fragments stretched more than a million kilometres through space. The comet was approximately 660 million km from the Earth when the picture was taken, on a mid-July collision course with the gas giant planet Jupiter (Courtesy of H.A. Weaver & T.E. Smith of the Space Telescope Science Institute, and NASA).

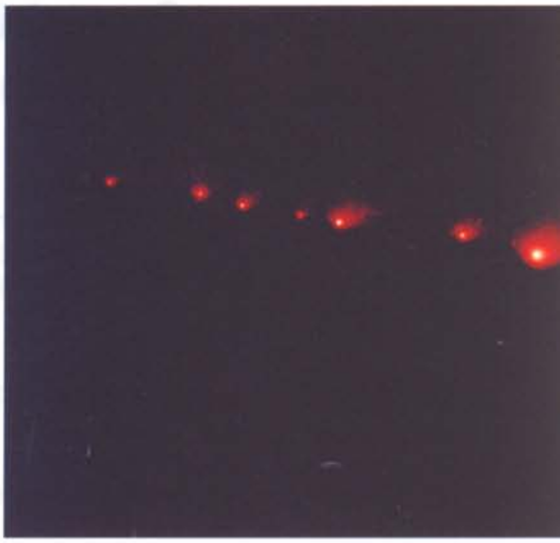
Theories of the development of life are highly uncertain, but the presence of massive bodies within a planetary system may be required to 'protect' the lower mass planets from cometary impacts. If such theories are correct, intelligent life may stand a much better chance of existing around stars with massive planetary systems which are, in turn, much easier to detect than lower-mass planets.

because of, these uncertainties, SETI-type searches (Search for Extraterrestrial Intelligence) have been running for a number of years.

Searches for planetary systems are basically concerned with the second and third terms of the Drake Equation. In recent years, as technology has advanced, 'planet hunting' has become a serious subject for astronomical research – not only in order to be able to estimate the number of locations in our Galaxy which may be capable of supporting life, but to a large extent because the subject is expected to throw further light on a key problem in astrophysics: the details of the origin of our own Solar System. Numerous questions related to this problem remain unanswered:
- How was our Solar System formed?
- Is planet formation a common or rare phenomenon?
- Is our Sun's single status (many, if not most stars are found in binary systems) related to the fact that it has a planetary system?

Even more complex 'cosmic coincidences' may be necessary for the development of advanced life forms. As a specific example, it is possible that the presence of at least one of the more massive jovian planets (Jupiter, Saturn, Uranus and Neptune) in the outer part of the Solar System was necessary for the development of life on Earth. The recent impact of Comet Shoemaker-Levy 9 with Jupiter in 1994 provided an outstanding illustration of why this might be so: Jupiter clearly acted as a gravitational 'vacuum cleaner', disrupting this particular comet on its previous visit to the Sun, and finally capturing it. This 'sweeping up' of cometary material must significantly decrease the possibility of a catastrophic encounter with the much less massive Earth, and in turn is likely to have permitted the ongoing, delicate evolution of life on Earth to develop (Fig. 1).

Planetary size may also be important for habitability; aside from the most obvious question of gravitational force on the planet's surface, long-term climatic stability requires (at



least on Earth) a mechanism for recycling of carbon dioxide from carbonate rocks back into the atmosphere: on Earth, this is done by plate tectonics, whereas much smaller planets would lack the internal heat necessary to sustain these motions.

Formation of our Solar System

Dating from the times of Laplace, but over the last few years in particular, an increasingly plausible picture has emerged as to how planetary systems like our own Solar System form. Present understanding is that they originate as a byproduct of star formation, with the gravitational collapse of material within high-density 'molecular clouds'. As gravitational infall proceeds, clouds that start off close to equilibrium under the combined effects of gravity, gas pressure, rotation, and magnetic fields, become more dominated by the effects of rotation, leading to the formation of a flattened disc. Details of the physical mechanism responsible for the formation of these 'accretion discs' remain uncertain, but it is thought that an outward transfer of angular momentum is accompanied by an inward flow of mass to form a young star – this disc is believed to be the seeding ground for the birth of planets that form in association with the star (Fig. 2).

Some current models are surprisingly specific: numerical modelling by G.W. Wetherill has

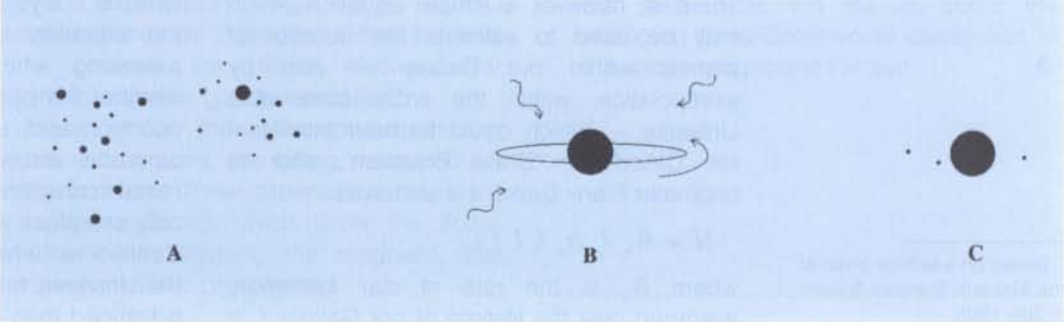


Figure 2. A highly schematic illustration of the possible formation of planetary systems: in (A) self-gravitating cores develop within interstellar molecular clouds; in (B) the young star, or proto-star, develops, fed by a nebular flattened disc and infalling material channelled towards it; in (C) as the infall terminates with the exhaustion of available material, the newly-formed star emerges along with planets formed from the material in the circumstellar disc.

suggested that the accumulation of 'planetisimals' during molecular-cloud collapse can be expected to produce four 'inner' planets on average – two being approximately Earth-sized and two smaller!

ESA's science mission ISO (the Infrared Space Observatory), launched on 17 November 1995, is expected to contribute significantly to studies and developing theories of these star and planet formation processes, since it can look, in the infrared, into star-forming regions which are, by their nature, highly obscured by the very 'dust' associated with their origins. ISO should also prove to be very useful in searches for extra-solar zodiacal light, as already known around the nearby star Beta Pic. Ground-based as well as Hubble Space Telescope observations have already been highly successful in imaging stars with proto-planetary discs (Fig. 3).

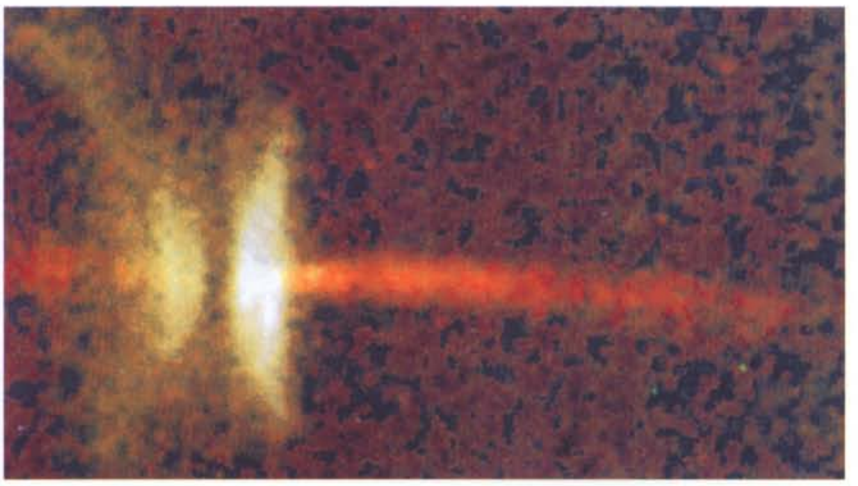
The search for planets

In astronomy, masses are usually and conveniently described in terms of the mass of our Sun: a 'solar mass'. It is considered that below about 0.08 solar masses, nuclear hydrogen fusion will not occur; masses below this and down to the 'deuterium-burning limit' of about 13 Jupiter masses are referred to as 'brown dwarfs' or, if lighter still, as super-planets or planets. (Jupiter weighs in at roughly one thousandth of a solar mass, the Earth being a further factor of 300 less massive still).

It has become generally accepted, largely from 'radial velocity searches' described below, that planetary systems, or at least systems with very massive planetary companions, are relatively rare. Nevertheless, a variety of direct and indirect detection methods have been undertaken in recent years, and with techniques rapidly improving, searches have intensified.

The astronomical world was greatly excited by the announcement last year of the first detection of a 'planetary mass' companion around a nearby solar-type star. Earlier this year, two further planetary candidates were reported, and additional suspects have been discovered even more recently. Somewhat surprisingly, the characteristics of these 'planets' were not quite what had been expected – in one case a very massive object was deduced to lie very close to the parent star, and uncomfortably so compared with existing theories of planetary formation. These theories are presently undergoing rapid re-appraisal, with spiralling in of a massive planet towards the parent star, after formation, being one possibility. Dramatic and fundamental though these discoveries are, it now becomes important to acquire information on further systems: as Dr David Black has commented in the Astronomy & Astrophysics Encyclopedia (van Nostrand Reinhold, 1992), *'Although the discovery of another planetary system would be exciting, significant scientific returns begin with the more difficult task of gathering statistical information. Only then will we be able to view the formation of our own planetary system in context.'*

Figure 3. This image of a protostellar object, called HH-30, was taken with the Hubble Space Telescope, and reveals an edge-on disc of dust encircling a newly forming star. Light from the star illuminates the top and bottom surfaces of the disc, making them visible, while the star itself is hidden behind the densest parts of the disc. The reddish jet emanates from the inner region of the disc, expanding for several billion kilometres from the star whilst remaining confined to a narrow beam. HH-30 is 450 light-years away in the constellation Taurus (Courtesy C. Burrows (STScI and ESA), the WFPC2 Investigation Definition Team, and NASA).



* 1 AU, or astronomical unit, is the mean distance between the Earth and the Sun; 1 parsec, or 3.26 light-years, is the distance at which one astronomical unit subtends an angle of 1 second of arc. The nearest star to the Sun lies at a distance of about 1 parsec, or 3×10^{13} km.

The problem is, of course, that planets are small and faint, and much smaller and fainter than the relatively massive and bright central star around which they orbit. The difficulties of 'direct' detection of a planet – where the radiation reflected or emitted by a planet is observed – is apparent when considering the case of Jupiter and the Sun: at visible wavelengths, the Sun is about a factor of one billion times brighter than Jupiter. At infrared wavelengths the contrast is less extreme, but still very significant. Searches for radio decametric emission from Jupiter-type objects are also planned.

There are about 250 stars within a distance of 10 parsec from our Sun, and at such a distance a Jupiter-type planet 5 AU from the Sun* would lie at a maximum distance of only 0.5 seconds of arc from the parent star. Observationally, this is a very difficult problem. It has been attempted, but realistically it is beyond the capability of even, say, the Hubble Space Telescope, for all but the very nearest stars. This is because of the HST's relatively small aperture, combined with static, small-scale wavefront errors. Future developments in ground-based 'adaptive optics', in which the telescope is deformed rapidly to adapt to the atmospheric effects which normally distort all ground-based images, may offer some possibilities, and the prospects in the infrared are more promising, especially for younger (and warmer) Jupiter-type planets. But the problem is still a daunting one. The proposed Darwin mission, submitted for consideration as part of the Horizon 2000 Plus programme (a similar concept is being considered by NASA as part of its 'Origins' programme) aims to detect this very faint infrared emission from a possible planet close to the target star. An interferometer with four or five cooled apertures, a baseline of 40 – 50 m, and placed well beyond the Earth's orbital distance from the Sun in order to avoid contamination from the Solar System's own zodiacal emission, would search for planetary candidates out to distances of 10 – 20 parsec from our Sun. Detection of Earth-mass, and not simply Jupiter-mass objects, may be feasible using this approach.

Part of the problem is knowing which of the stars should be targetted for such a careful search! Nevertheless, a Darwin-type mission could aim to include a still more ambitious goal: specific spectroscopic features, for example the ozone line at 9.6 microns, would be possible indicators of an atmosphere out of chemical equilibrium – and thus an indication of the possibility of life. Other constituents, such as CO_2, H_2O, or O_2, could be searched for (although not necessarily by the Darwin mission), on the grounds that they are either essential for (aerobic) life, or produced by life.

Whilst direct imaging of planetary systems is likely to remain challenging for the foreseeable future (and the difficulty increases for stars further away, partly because the planetary system becomes ever closer in angular separation from the parent star) astronomers have investigated other possible search methods. In one, the effect of the planet is inferred by 'occultations' as it passes across the face of the star, leading to a temporary and very tiny decrease in brightness of the target star (Fig. 4). The geometric probabilities of such an event being observable (the ratio of the stellar diameter to the orbital radius), and the resulting drops in the observed intensity of the star (the ratio of the area of the planet to that of the star), can be simply calculated: for an Earth-like planet, the probability of the event being observed is about 0.5 percent, the brightness decrease is about 1 part in 10 000, and the event duration is about 13 hours; for a planet the size and orbital distance of Jupiter, the numbers are 0.09 percent, 1 part in 100, and 25 hours duration, respectively. Interestingly, the

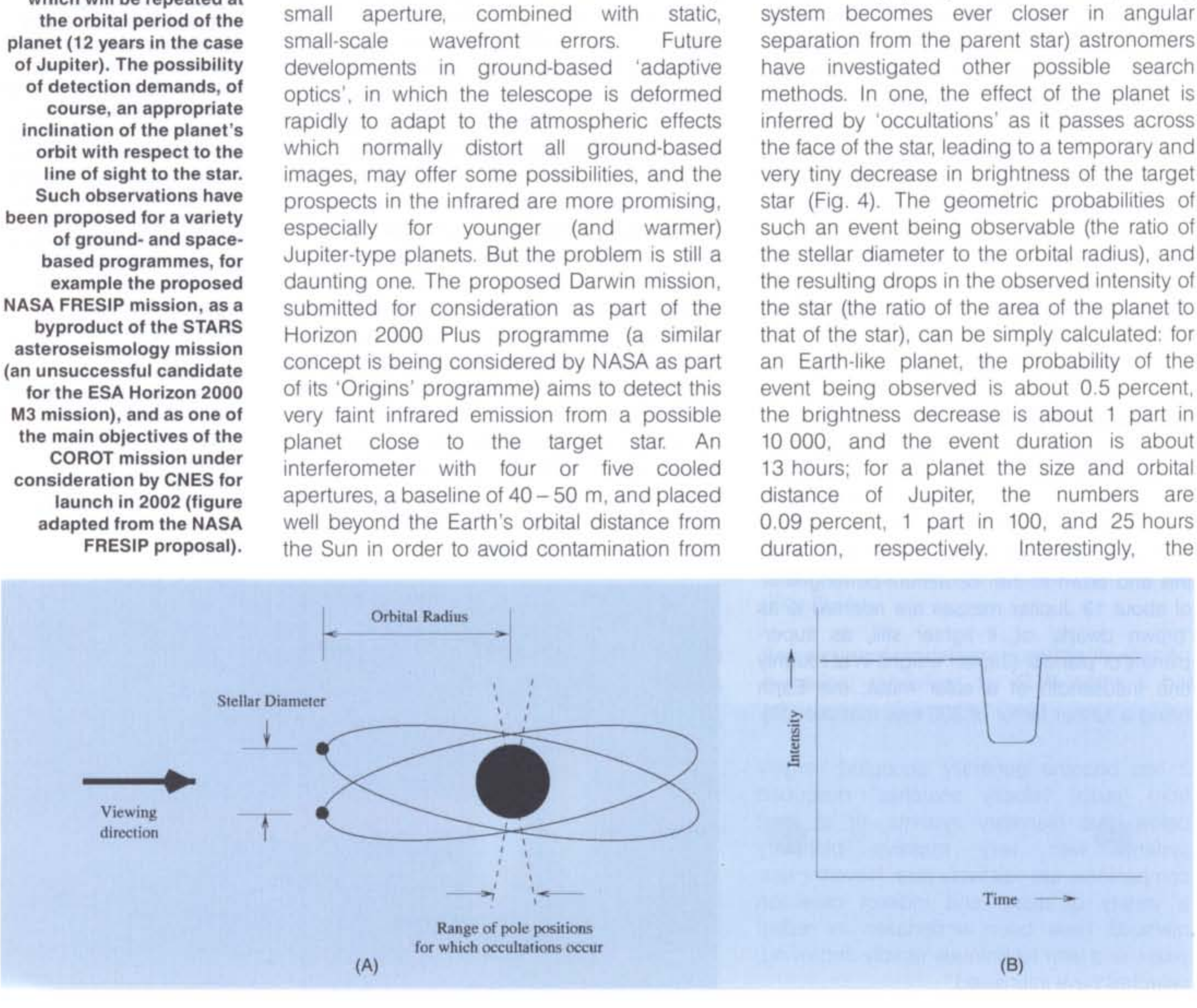


Figure 4. Principle of detection of an extra-solar planet around a star by occultation. The planet passes across the face of the star (A), resulting in a characteristic time-dependent signal (B), which will be repeated at the orbital period of the planet (12 years in the case of Jupiter). The possibility of detection demands, of course, an appropriate inclination of the planet's orbit with respect to the line of sight to the star. Such observations have been proposed for a variety of ground- and space-based programmes, for example the proposed NASA FRESIP mission, as a byproduct of the STARS asteroseismology mission (an unsuccessful candidate for the ESA Horizon 2000 M3 mission), and as one of the main objectives of the COROT mission under consideration by CNES for launch in 2002 (figure adapted from the NASA FRESIP proposal).

method yields the size of the planet directly. In the near future, astronomers will get a better understanding of whether these searches will be successful.

Another interesting possibility is detection by gravitational lensing. Gravitational lenses are a prediction of general relativity, and were first observed in astronomy in 1979, some 60 years after the first detection of gravitational light deflection by the Sun. Since then, the subject has flourished, and lenses potentially provide a powerful probe of 'dark matter' now believed to dominate the mass of the Universe. 'Microlensing' events are presently being actively searched for from the ground, with the main aim of detecting very faint, very low mass objects, possibly constituting the dark matter, which would otherwise remain invisible, but which can be seen due to the gravitational influence on the light of the background stars.

Several microlensing candidates have recently been detected from the ground, with durations ranging from several hours to several days, and with characteristically smooth, bell-shaped light curves. A planet would produce an 'aberration' in the otherwise symmetrical lensing action of a star, causing an irregularity in the brightening of the background object, and thus producing a sharp additional peak in the light curve superimposed on the smooth background brightening. The effect is maximised for orbital radii near the so-called 'Einstein radius'; for searches now going on in the bulge of our Galaxy, this corresponds to a linear distance of a few astronomical units – fortuitously close to the orbital radii predicted for giant planets. The effect is large: several percent of the main peak in the case of Earth- to Jupiter-sized planets, with durations extending from several minutes up to about one day.

Spectroscopic and astrometric searches for extra-solar planets

There are two further well-established methods, with a common physical effect, which can be used for indirect detection. If a star has a companion, the centre of mass of the system is displaced from the centre of mass of the star. In the case of our Solar System, the centre of mass is dominated by the jovian planets, and describes a complex motion with respect to the centre of the Sun, according to the relative positions of all of the other objects in the Solar System. Taking a simple example of a single massive planet orbiting a star in a circular or elliptical orbit, the star undergoes its own 'reflex' motion about the centre of mass of the system (Fig. 5). This 'wobble' of the parent star can be detected in two ways – either using spectroscopy of the system (dominated by the light of the central star) to reveal Doppler line shifts corresponding to the line-of-sight component of the orbital motion relative to the observer, or more directly through astrometric measurements. The latter aim to measure the positional displacement of the star from the system's barycentre at successive times – while the centre of mass of the system moves linearly through space, the star will oscillate about it. Both methods can measure the period of the orbital motion. The spectroscopic method has a disadvantage that the effect is dependent on the angle between the line-of-sight and the orientation of

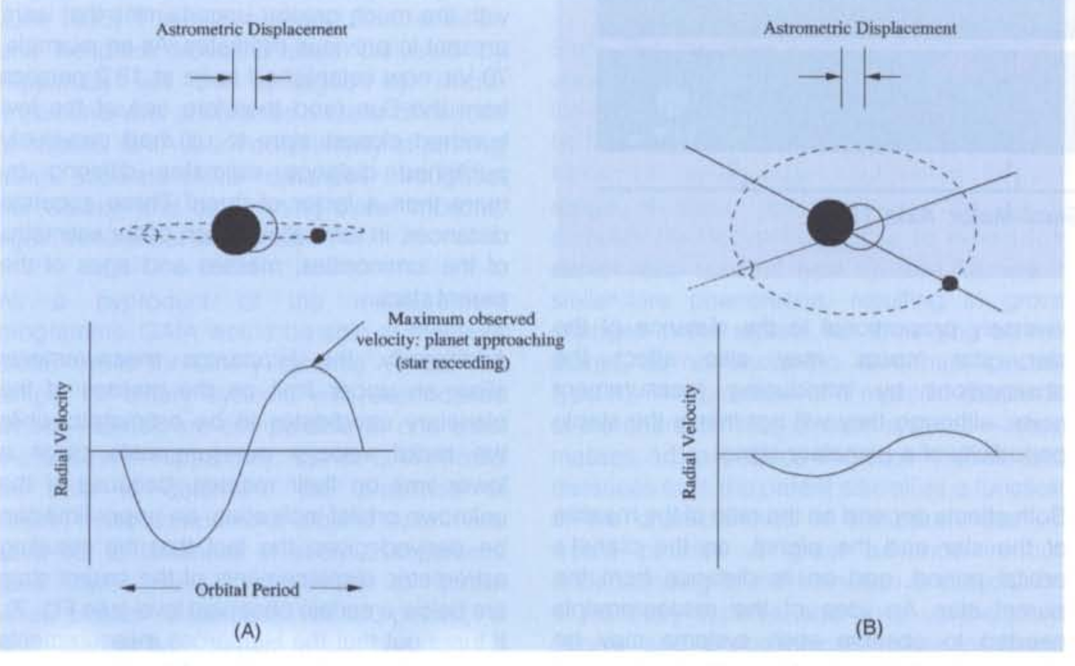


Figure 5. As a planet orbits the parent star, the centre of mass of the system moves with respect to the centre of mass (and centre of light) of the star. The effect results in a periodic Doppler motion of the spectrum of the star as the component of its motion moves back and forth along the line of sight. It also results in an elliptical displacement of the star's position with respect to the centre of mass of the system. In (A), where the orbital plane is almost along the line of sight, the (spectroscopic) Doppler motion is of maximum amplitude. In (B), where the orbital plane is almost face-on to the line of sight (in the plane of the sky), the Doppler motion largely vanishes. In both cases the (astrometric) oscillatory motion of the parent star can be observed by measuring the position of the star as a function of time.

the orbital plane of the planetary system, so that a system viewed face-on will show no Doppler component. Also, stars display a variety of phenomena related to rotation and pulsation that may mimic true Doppler shifts. On the other hand, the minimum mass detectable for astrometric displacements is inversely proportional to the distance of the star; star 'spots' may also affect the observations by introducing measurement noise, although they will not mimic the stable periodicity of a planetary signal.

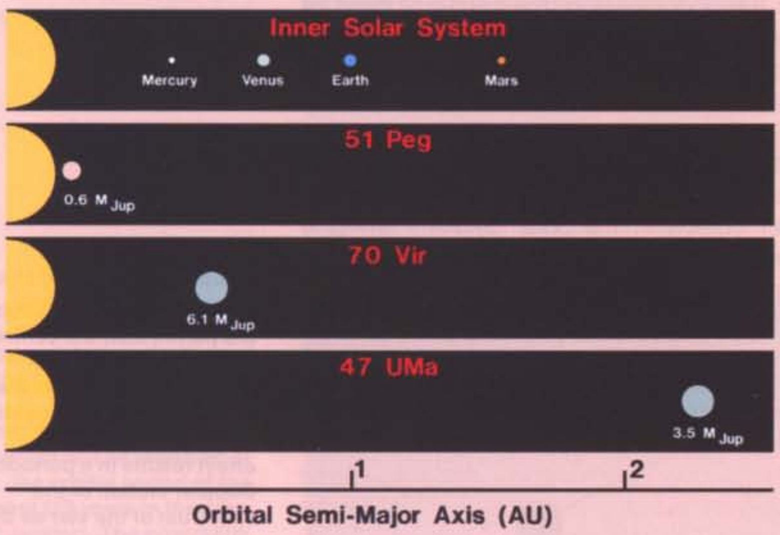


Figure 6. Extra-solar planets are now known to surround the three stars, 51 Peg, 70 Vir, and 47 UMa. This figure shows how these systems compare in mass, and distance from the parent star, compared to the case of the Sun and Jupiter (taken from the work of G.W. Marcy and R.P. Butler, by kind permission of the authors). The proximity of the massive planet surrounding 51 Peg to its parent star was unexpected (models had not predicted that such massive planets could be formed so close to the star) and has already led to vigorous debate about the formation and evolution of the more massive planets. Note that the three candidates are each several Jupiter masses, and all therefore more than a factor of one thousand more massive than the Earth. The distance of the planet surrounding 70 Vir from its parent star is such that its expected surface temperature could be in the range necessary for water to exist in liquid form, at least for part of the orbit.

Both effects depend on the ratio of the masses of the star and the planet, on the planet's orbital period, and on its distance from the parent star. An idea of the measurements needed to observe such systems may be obtained from the situation with the Sun and Jupiter: the Sun's velocity oscillates with an amplitude of 12 m/s, and a period of 12 years, due to the presence of Jupiter. To detect this type of motion in other stars requires spectroscopic measurements of very high accuracy, using instruments that are stable over many years. Such measurement programmes have been going on for several years at different ground-based observatories, and these efforts were rewarded when the first positive detection (in the case of the star 51 Peg) was announced by M. Mayor and D. Queloz from the Geneva Observatory last year; confirmation and two further candidates (47 UMa and 70 Vir) were reported by G.W. Marcy and R.P. Butler (San Francisco State University) earlier this year. High-precision radial-velocity measurements pinned down the periods, masses, and semi-major axes of the planetary orbits. Strictly, the mass estimates derived by this method are only lower limits in view of the unknown orbital inclination of the systems with respect to the line of sight. The likely configurations of the resulting systems are illustrated in Figure 6.

Results from ESA's Hipparcos astrometry satellite have already made an interesting contribution to this topic. Accurate distance measurement to stars within a few hundred parsecs of the Sun is a very difficult problem, and only the advent of space techniques has put these measurements on a secure observational footing. The three planetary candidates are among the more than one hundred thousand stars in the Hipparcos Catalogue; the distance to each is now established with an accuracy of about 1 percent, which compares very favourably with the much greater uncertainties that were present in previous estimates. As an example, 70 Vir, now established to lie at 18.2 parsecs from the Sun (and therefore one of the few hundred closest stars to us) had previously published distance estimates differing by more than a factor of three! These accurate distances, in turn, allow much better estimates of the luminosities, masses and ages of the parent stars.

Additionally, the Hipparcos measurements allow an upper limit on the masses of the planetary candidates to be estimated: while the radial velocity measurements place a lower limit on their masses, because of the unknown orbital inclination, an upper limit can be derived given the fact that the resulting astrometric displacements of the parent stars are below a certain observed level (see Fig. 7). It turns out that the Hipparcos measurements confirm that in at least two of the three cases, the companion masses are well below the hydrogen burning 'brown dwarf' mass limit, and indeed satisfy the semantic criterion for classifications as planets.

(Very high precision astrometric measurements are also now being made for radio stars, using the ground-based technique of Very-Long-Baseline Interferometry. Sophisticated 'timing' techniques can also be applied to radio pulsars and eclipsing binaries (binary star systems in which the secondary is revealed as a result of light eclipses of the primary star), where uniformally spaced signatures of the underlying spin or orbital motion will be perturbed by additional orbiting companions. However, in all of these cases, the parent stars are unlikely to provide a suitable environment for the development of life.)

The future, and the GAIA mission

The next few years are likely to see the detection of further planetary systems, most probably from continued radial velocity searches, and rapid developments in the understanding of the formation and evolution of planetary systems. However, the detection of Earth-mass planets is likely to remain problematic from the ground for the foreseeable future. In addition to the proposed space missions Darwin and COROT, where the detection of such objects is a primary goal, space astrometry provides dramatic possibilities for the further detection of planetary systems. The proposed GAIA project is a 'super-Hipparcos' astrometric mission employing a scanning satellite, a fixed-baseline optical interferometer, and an advanced detection system (see ESA SP-379, 'Future Possibilities for Astrometry in Space', June 1995). The milliarcsecond accuracies on one hundred thousand stars delivered by Hipparcos will be upstaged by microarcsecond-level accuracies on tens of millions of objects. GAIA is aimed primarily at pinning down accurate stellar distances throughout our Galaxy, and determining stellar motions, again throughout the Galaxy.

As a byproduct of the measurement programme, GAIA would be able to measure stellar orbits for binary systems – but not simply for binary systems with secondaries whose masses are comparable to one solar mass (as with Hipparcos). Rather, GAIA would be able to determine the presence of Jupiter-mass companions around solar-mass stars out to distances of about 200 parsecs (and lower mass companions to somewhat smaller distances). At 100 parsec, a Sun – Jupiter type system would result in an astrometric displacement of the star of about 50 microarcsec. While an Earth-like planet around a solar-mass star at 10 parsec would result in a displacement of only 0.3 microarcsec, with very good metrology, the detection of a few Earth-like planets is not beyond the realms of possibility for a mission like GAIA. Multiple planets around a given star will create additional problems in understanding the system.

Within the volume of space corresponding to a distance horizon of 200 parsec (our Galaxy is some 30 000 parsec in diameter), there exist some 500 000 stellar candidates. If the occurrence of planets around other stars is a rare phenomenon, progress from the ground over the next few years will be a slow and laborious process, and GAIA would revolutionise the search. If the phenomenon is more common, GAIA could determine thousands, or tens of thousands, of such systems.

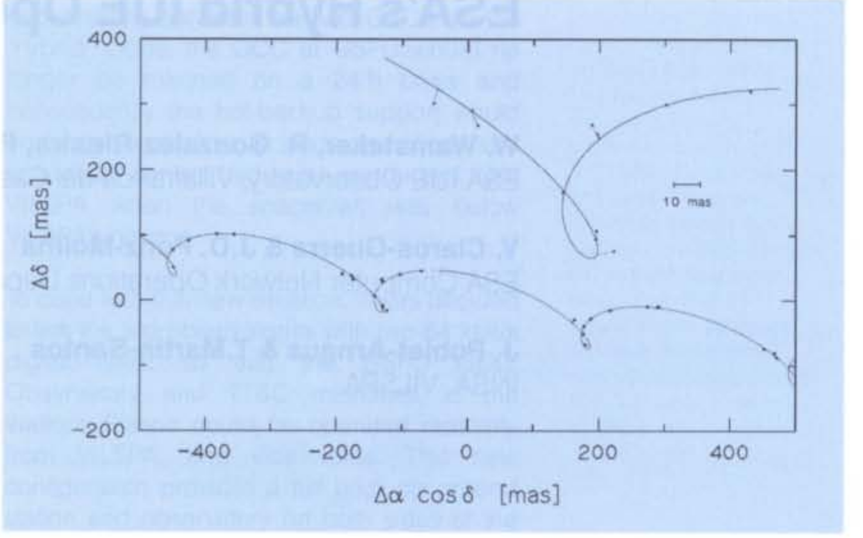


Figure 7. The path of 47 UMa (HIP 53721) across the sky, over a period of three years, determined by Hipparcos. The dots indicate the observed position at each moment of observation, with residuals indicated by the straight lines joining the dots to the modelled stellar path (solid line) at the corresponding epoch. The expanded region (top right) corresponds to the second 'loop', where the deviations between the elemental observations and the fitted curve are more evident. The amplitude of the oscillatory motion gives the star's parallax, or distance. The star has a proper motion of approximately −0.3 arcsec/yr in right ascension. The deviations of the observed positions from the smooth curve set limits on the mass of any companion object circling the star.

Stars like the Sun may have planets with conditions conducive to the development of life in the so-called 'habitable zone': bounded by the range of distances from the parent star for which liquid water would exist, by the range of stellar spectral types for which complex life had enough time to evolve (no earlier than spectral type F), and for which stellar-flare phenomena, resulting in gross changes in the radiant flux impinging on the planet, do not occur (no later than spectral type K). The provision of a massive databank of the characteristics of such systems – their masses, orbital periods and eccentricities, and distances from the parent star, all as a function of the characteristics of the parent star – would promise a great advance in our understanding of the formation and evolution of planetary systems, and open up the more elusive and philosophically more profound terms of the Drake Equation. The statistical results would provide the necessary basis for more ambitious satellite missions, aimed at direct imaging and spectroscopy of stellar companions. The understanding of whether we are alone in the Universe would make one more significant step forward.

Further details of some of the topics covered in this article can be found at various WWW sites:

— for the candidate Horizon 2000 Plus cornerstone missions Darwin and GAIA, see

http://ast.star.rl.ac.uk/darwin/ &
http://astro.estec.esa.nl/SA-general/Projects/GAIA/gaia.html,

respectively.

— for further details of planetary search programmes, see

http://www.obspm.fr/planets &
http://cannon.sfsu.edu/~williams/planetsearch/planetsearch.html.

ESA's Hybrid IUE Operations

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As a project that opened up a new era in space astrophysics, IUE has of course had many 'firsts' during its eighteen years of orbital operation. However, there have been some truly unique accomplishments in the context of the IUE project that must be recognised as real innovations in space science and space engineering. The latest occurred shortly after the decision to terminate the project in September this year.

The failure of IUE's no. 5 gyroscope on 6 March this year and the subsequent reconfiguration of the spacecraft control mode mean that it is the first three-axis-stabilised spacecraft to be operated with only one functional gyroscope.

Other project highlights include the fact that:
- **IUE has provided the first** *worldwide* **astronomical** *reduced-data* **archive delivering 44 000 spectra per year – 5 every hour – to astronomers in 31 countries**
- **IUE is the first astronomical facility to deliver fully reduced data within 48 hours of observation to the worldwide scientific community.**

Introduction

After 18 years of annual extensions of its activities, the International Ultraviolet Explorer (IUE) Observatory has become a familiar hands-on facility to the worldwide astronomical community. The IUE project, run by NASA, ESA and PPARC (UK), has been the subject of an unprecedented response from the scientific community, in terms of both direct data acquisition and the use made of its data archive.

The worldwide scientific community was therefore very much surprised in December 1994 by the recommendation from a NASA Senior Review Panel, evaluating astrophysics projects on a 'science per US $' basis, that IUE orbital operations should be discontinued. Since European astronomers felt that such an ad-hoc termination would be damaging to ultraviolet astrophysics, the ESA IUE Project proposed a solution via a complete revision of the operations and science support procedures, which by then had been running successfully for eighteen years.

The resulting 'hybrid' operating mode has been designed to reduce overall project costs to a minimum in order to perform a 'Final IUE Science Programme'. Due to the timing of all this and the different funding cycles, negotiations, technical developments, user information distribution, funding needs evaluation etc., it became a race against the clock. Various pre-studies to evaluate improvements in efficiency had already been made at the ESA IUE Observatory in previous years. In January 1995, ESA's Astronomy Working Group expressed strong support for the suggested termination of orbital operations in an orderly manner at the end of 1997. However, the situation changed significantly as a result of the financial reductions imposed on ESA's Science Programme at the Ministerial Council Meeting in Toulouse in October 1995. The recommendation by the Space Science Advisory Committee (SSAC) to terminate IUE orbital operations not later than September 1996 was endorsed by the Science Programme Committee (SPC) in February 1996.

This is therefore an appropriate moment to highlight the most significant changes made in the context of the 'hybrid' IUE operations which had fully rejuvenated the long-running project and could serve as 'lessons learned' for future scientific mission operations.

Aspects of the operations that were redefined and streamlined in a significant way included:
- Time allocation: A joint Allocation Committee was formed under the Chairmanship of Prof. K.S. de Boer (University of Bonn) where, for the first time, all IUE applications were evaluated jointly by the three Agencies.

- Time distribution: Time is no longer allocated in 8 h shifts to a Principal Investigator (PI). Time for observations is requested and the ESA IUE Observatory makes a commitment to perform the approved observations when spacecraft constraints and scientific requirements allow.
- Observing time and science operations: The 24 h operations have been reduced to the 16 h corresponding to the high-quality part of the orbit, and all are performed from the ESA IUE Observatory. For the remaining 8 h when the spacecraft is around perigee (where science capabilities are severely limited by the particle radiation background), only minimal spacecraft control is applied from NASA's Goddard Spaceflight Center (GSFC). A small fraction of the 24 hour observing periods has been retained for special science requirements.
- Observer presence: The normal Principal Investigator presence has been suppressed and science observations are conducted in service observing mode only.

These changes meant that all procedures had to be reviewed and activities revised in order to construct an economically and scientifically effective compromise. It is not feasible here to cover all the changes that have taken place, but we will focus on those in the areas of spacecraft control (TT&C), observatory functionality, as well as data processing and distribution (in parallel with the reprocessing of the more than 100 000 images already taken by IUE). The overall result is a modern up-to-date space observatory based on state-of-the-art hardware, software and communications capabilities.

Telemetry, Tracking and Telecommand (TT&C)

The original IUE system comprised the spacecraft in geosynchronous orbit and two self-contained ground stations and 'observatories' equipped with subsystems for telecommand uplinking to and telemetry downlinking from the spacecraft. Ranging or tracking was only possible from the Wallops ground station as NASA was responsible for maintaining the spacecraft's orbit. Under this configuration, NASA exploited the satellite for 16 h/day and VILSPA for 8 h/day and the two observatories operated nearly independently. The Operations Control Center (OCC) located at Goddard Space Flight Center monitored the spacecraft on a 24-hour basis and served as a back-up to VILSPA for potential single-point failures (main computer system and VHF command antenna). The only communications link was a voice line for coordination between the two OCCs. In the 'hybrid' mode, the OCC at GSFC would no longer be manned on a 24 h basis and consequently the hot-backup support would no longer exist. Also, science operations and spacecraft control had to be conducted from VILSPA when the spacecraft was below VILSPA's horizon.

To cope with this new situation, it was decided to link the two observatories with two 64 kbit/s digital lines, so that the GSFC OCC, Observatory and TT&C interfaces to the Wallops Station could be operated remotely from VILSPA, and vice versa. This new configuration provides a full back-up ground station and observatory on both sides of the Atlantic, making local duplication superfluous. This new modus operandi is termed 'bent-pipe operations'. In coordination with ESOC, VILSPA designed the new configuration (Fig. 1) and built and installed the necessary equipment both at VILSPA and GSFC. ESOC also made the necessary provisions in Darmstadt and configured the VILSPA and GSFC communications nodes so that the IUE 'hybrid' operations could be started on 1 October 1995.

The IUE communications in 'bent-pipe' mode are based on:

(a) two 64 kbit/s digital links, on diverse routings between VILSPA and GSFC
(b) two 9.6 kbit/s digital channels on the general-purpose VILSPA – ESOC and ESOC – GSFC 64 kbit/s links
(c) one Public Switched Telephone Network (PSTN) connection as an emergency back-up link.

The core units for these 'bent-pipe' operations are:

- the Interface, Switching and Logic Unit (ISLU), designed and built at VILSPA
- the Telescope Operations Console/ Telemetry (TOCTM) switching unit, designed and built at VILSPA, and
- the Statistic Data Multiplexer Units (STDM) (off-the-shelf).

The ISLU unit allows either side to remotely operate the Σ-9/5 or T-85 computers at GSFC or VILSPA, respectively, so that TT&C operations can be performed using the ground station located on the other side of the Atlantic using only a 9.6 kbit/s bandwidth channel.

The TOCTM unit allows VILSPA to remotely operate the GSFC Telescope Operator Console and perform science operations remotely, i.e. to prepare and read IUE's

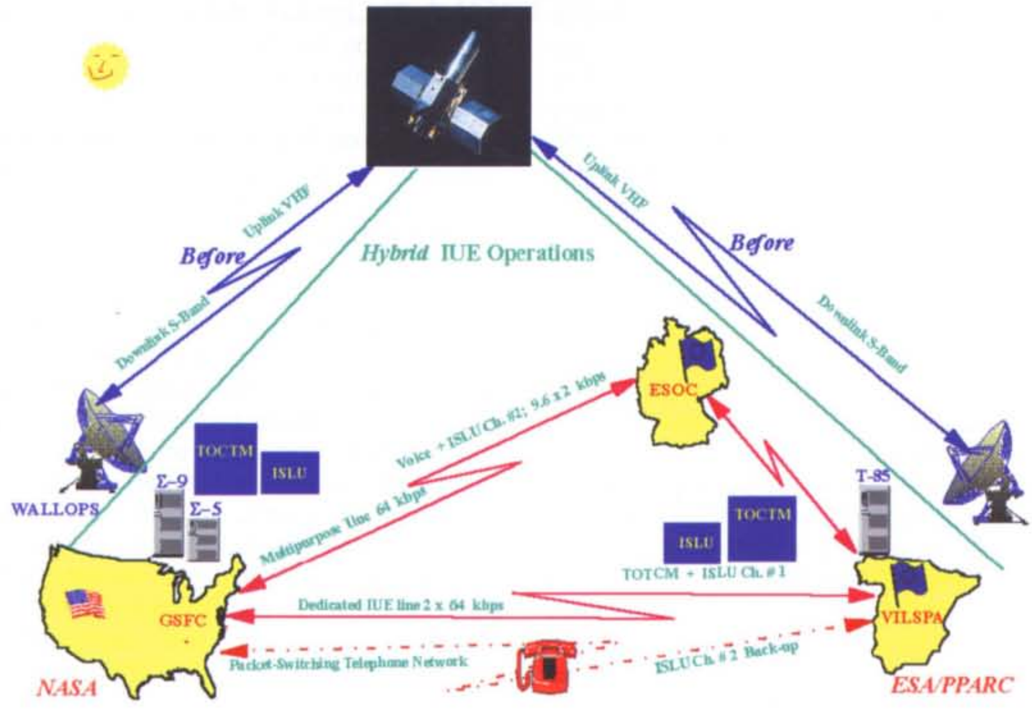

Figure 1. This diagram illustrates the 'hybrid' TT&C configuration, showing the extended communications configuration put in place to support the 'hybrid' IUE science operations. The blue arrows show the original situation, and the blue boxes show the VILSPA-developed hardware which allows complete mutual hot back-up between the two control centres (VILSPA and GSFC)

on-board spectrograph and relay the images to Villafranca where they can be processed. Also, this unit can be used to bring raw telemetry to the station when there is a failure on the VILSPA front-end system or when the spacecraft controllers at VILSPA need to monitor manoeuvres performed by the spacecraft when operating via Wallops.

With this infrastructure installed, up to 16 different modes of operation can be selected. The three most important are:

(i) VILSPA local operations
In this configuration, no data link to GSFC is required except the voice link (via ESOC) to coordinate with the Data Operations Controller (DOC) permanently present in GSFC, who provides back-up support via Wallops in the event of a failure in VILSPA's ground computer.

(ii) Bent-pipe operations
In this configuration the OCC is manned at VILSPA and the satellite is operated using the GSFC computer system and Wallops ground station. Communications for the ISLU operations, voice, and reception of scientific and/or telemetry data requires: two 64 kbit/s links, one voice coordination channel and prime and back-up ISLU channels (prime on VILSPA – GSFC link and back-up on VILSPA – ESOC – GSFC link).

(iii) Operations in failure situations
The ISLU system allows VILSPA to continue spacecraft operations even if the unique IUE T-85 computer goes down. It permits remote commanding of the spacecraft via Wallops, thereby providing a back-up to the single-point-failure VHF SATAN command system.
The TOCTM unit allows VILSPA to receive raw telemetry from Wallops, and process it to display manoeuvre parameters, providing a full front-end back-up. The TOCTM also allows VILSPA to operate a Telescope Operator Console at GSFC remotely, thereby providing a full back-up to scientific operations at VILSPA.
The PSTN modem provides emergency by-passing of the GSFC communications node in the case of failure (this node constitutes a single-point failure as both ISLU channels are routed through it).

The installed system is fully bi-directional for the GSFC OCC and the VILSPA OCC Science Operations Centre. The system design is very flexible and efficient, as it has it has been based on the existing equipment in both OCCs, thereby minimising the number of new items to be manufactured or purchased off-the-shelf. The engineering was done by VILSPA's maintenance and operations engineers, which also kept the total financial outlay low.

The observatory

In order to implement the 'hybrid' operations approach, the observatory organisation and working schemes (i.e. user interfacing, science observation and data delivery) were completely revised, from proposal submission, through data processing, to product delivery. The new schemes (Figs. 1 – 3) contain innovations in many aspects, the most far-reaching ones being the suppression of the time allocation in 8-hour shifts to a single Principal Investigator (PI) and his/her presence during the observations, and the electronic delivery of data. All of these changes were necessary to optimise the scientific output of the instrument and to minimise costs, without requiring an unreasonable effort from the users to accommodate the new scheme.

The application of new technologies in various areas has allowed a more automated and direct flow of information between the users and the observatory, both for preparing the observations and for retrieving the data (Fig. 2). To replace the standard mailing of large proposal packages, a system of electronic proposal submission and processing was implemented. Once processed, the proposals were forwarded to the members of the Joint IUE Allocation Committee (J-IUEAC) for scientific evaluation, and reviewed by the scientific staff of the observatory for technical feasibility. This technical review was also communicated to the J-IUEAC, so ensuring timely availability of all of the information needed for proposal evaluation.

As soon as the approved observations were defined by the J-IUEAC, a master observation file was generated, including target coordinates, instrument setups and other scientific or coordination requirements which could affect the scheduling. This master observation file was then transferred to a Pre-observation Preparation System, where an automatic query to the HST Guide Star Catalogue and the Digitised Sky Survey provided a choice of guide/offset stars and finder fields for all targets. Contact Resident Astronomers, assigned to every programme, informed the PIs of any possible problems affecting their observations and the full details were clarified, taking into account the actual time allocation by the J-IUEAC. A final file containing all the targets to be observed, together with the information necessary to perform the observations (e.g. specific spacecraft command sequences), was loaded into the real-time operations software. This same information was also introduced into the scheduling system, which determined a first-order optimisation of the observation date according to: (a) the spacecraft constraints (mainly related to power availability and subsystem temperature restrictions); and (b) the scheduling requirements of the PIs, such as specific dates and/or intervals between observations, due either to the nature of the target (e.g. a binary system), or to the need for coordination with other spacecraft and/or ground observations (necessary for 36% of the programmes).

During the observation preparation, PIs were also requested to specify their preferences for data distribution. An associated data-distribution master file was then prepared for inclusion in the Data Processing and Distribution System, which ensured delivery of the output data in accordance with the PI's request (address, media, frequency ...).

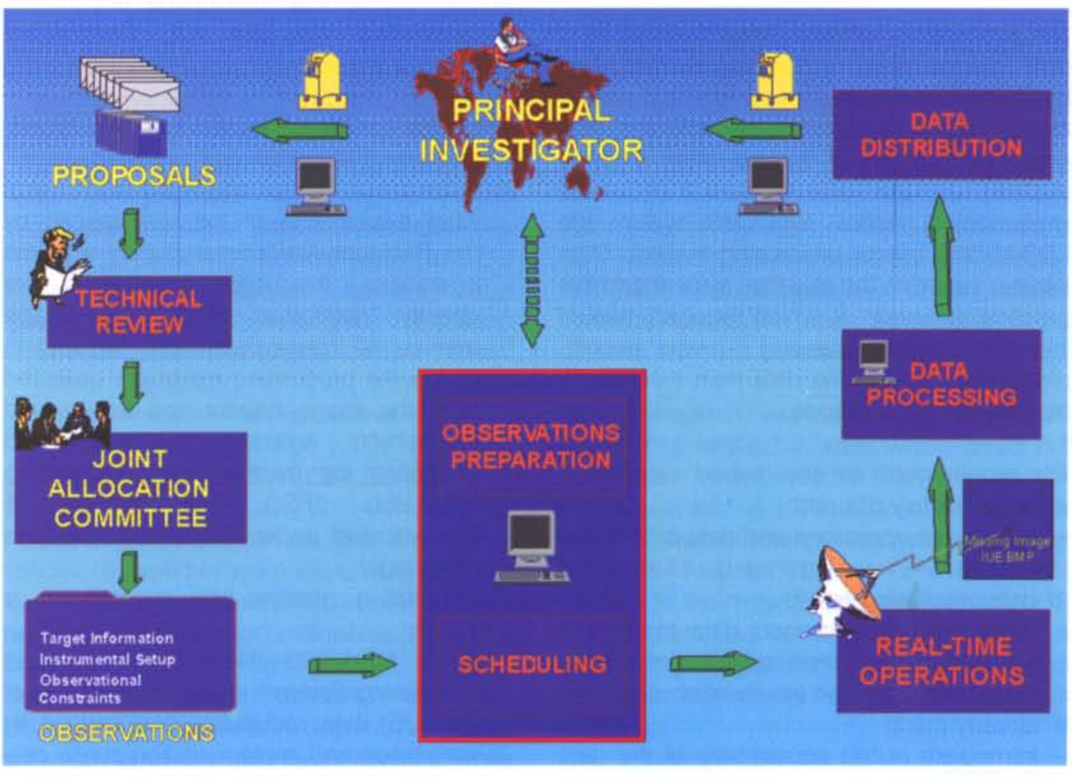

Figure 2. Overall information flow from the proposal cycle to data delivery in the 'hybrid' IUE configuration, relying on modern electronic means wherever possible to streamline the data flow

When the observations are performed, the raw data are transferred electronically from the real-time computers to the image processing systems, where they are processed and archived. The processed data are automatically loaded onto magnetic disks for self-retrieval by the PI via electronic networks (they can also be sent by post, on request). The design of these systems has made all the information needed for the observations available electronically at the console of the Telescope Operations Computer; there, the sequence of commands to be uplinked to the spacecraft can be retrieved from a database, but it can also be modified or even interrupted in real time. This maintains the necessary flexibility in the science operations, so that decisions can be taken quickly based on prevailing circumstances. This scheme of working means that target-of-opportunity observations can still be easily accommodated, and any unexpected astronomical event can be observed within a few hours.

Data handling

From the beginning of the IUE project, IUE data handling at VILSPA was driven by:
- 8 hours per day of science operations
- 16 hours per day of image processing and maintenance
- PIs being assigned 8-hour shifts of observing time for their programmes
- PI presence during the observing shift
- IUE data delivery on 9-track tapes, paper plots and photowrites
- proprietary rights for 6 months, after which the data became public.

The processing software, known as IUESIPS (IUE Spectral Image Processing System), had been upgraded many times and at first shared the same hardware with the IUE real-time computer system (Σ-9 and later T-85 at VILSPA). In the late '80s, IUESIPS was implemented under VAX/VMS within the ESO-MIDAS image processing system. Data transfer between the real-time system and the processing system – which required manual intervention for processing – was accomplished by copying the data from machine to machine on 9-track tapes.

The requirements for the 'hybrid' operations were completely different:
- no science operations and data processing in the USA, resulting in a doubling of the data-processing needs
- rapid flow of processed data to the PIs to allow programme adjustments as a consequence of the results of observations already made
- immediate public accessibility of the data (no proprietary period)
- integration of the operations data flow into the processing data flow to allow direct incorporation of the data into the IUE Final Archive, avoiding the need for a complete reprocessing of the data taken in the (current) 19th Episode before archiving.

The service observing mode requires integrated scheduling. The observations are scheduled solely to optimise satellite operations, science requirements and observing efficiency, rather than by programme and observing shift. It was therefore necessary to re-design all data-handling procedures, implementing a highly streamlined processing pipeline all the way into the quality-control procedures and data-distribution mechanisms (Fig. 3). The boundary conditions for this were:
- a very tight schedule
- minimal software system development (i.e. use of existing commercial products where available)
- implement new technology available to the user community also
- minimise manual intervention in the operational workload
- a new user community (the US astronomers previously supported by NASA).

This was quite a challenge, because the new systems had to be implemented while the old operations continued. In fact, the transition from the old 'classical' to the new 'hybrid' operations took place on 30 September 1995 at 23 h UT without interrupting any of the services that the ESA IUE Observatory provides to its users.

The data-handling system for the 'hybrid' operations consists of three main subsystems:

(i) Input data collection and first quality control
After examination of the raw images by the Resident Astronomer during real-time operations, the IUE observations are directly transferred to the raw image archive. All image parameters required to define the processing mode are collected from the image header and are verified interactively against the hand-written observing log by the Image Processing Specialists (IPSs). This process is implemented under IDL (Interactive Data Language).

(ii) Processing pipeline and second quality control
Since NEWSIPS (New Spectral Image Processing System), a complete re-write of the IUE data reduction, has passed its verification and implementation phase only

for low dispersion data, two processing pipelines had to be installed: one for IUESIPS for high-dispersion spectra, implemented under VAX/VMS, and one for NEWSIPS for low-dispersion observations, implemented under a distributed UNIX environment consisting of processing nodes. Output files are generated in the standard astronomical data-transfer format (FITS).

The verified image parameters (CDI = Core Data Items) are used to appropriately process the spectra and are directly ingested into a master database installed under ORACLE7. These parameters can be accessed via Standard Query Language (SQL) or a WWW browser, allowing one to maintain the operational data archive and to keep track of all IUE observations accomplished. This database also informs users of the availability of the data immediately after processing.

After a second quality control, all output products are archived and transferred to the data-distribution subsystem, described below. On request, the files can also be delivered on high-density tapes (DAT or Exabyte) to users wishing to have access to all of the data-reduction stages (e.g. for specialised processing).

(iii) Data distribution

Extracted spectra are available on-line at the distribution node

IUEARC.VILSPA.ESA.ES

classified by programme. Although the original commitment was to deliver the data within 14 days of the observation, in most cases the processed spectra are available on-line within 48 h. Data retrieval by the scientists themselves is done using either anonymous FTP or a WWW browser. Due to storage-space limitations, only the extracted spectral data are available (i.e. the high-dispersion Echelle orders and the low-dispersion spatial spectra and extracted arrays). Additional information and support is available on the WWW server dedicated to the 'hybrid' IUE operations in the 19th Episode at

HTTP://WWW.VILSPA.ESA.ES/IUE.19th.

A special effort has been made to ensure that spectra delivered in these ways, from both the NEWSIPS and the IUESIPS software, can be handled by major astronomical image-processing systems. For example, the IUE Data Analysis Center (IUEDAC) at GSFC developed a new version under IDL to deal with high- and low-dispersion spectra, while the latest version of ESO/MIDAS (95NOV) includes an 'IUE context' developed at VILSPA.

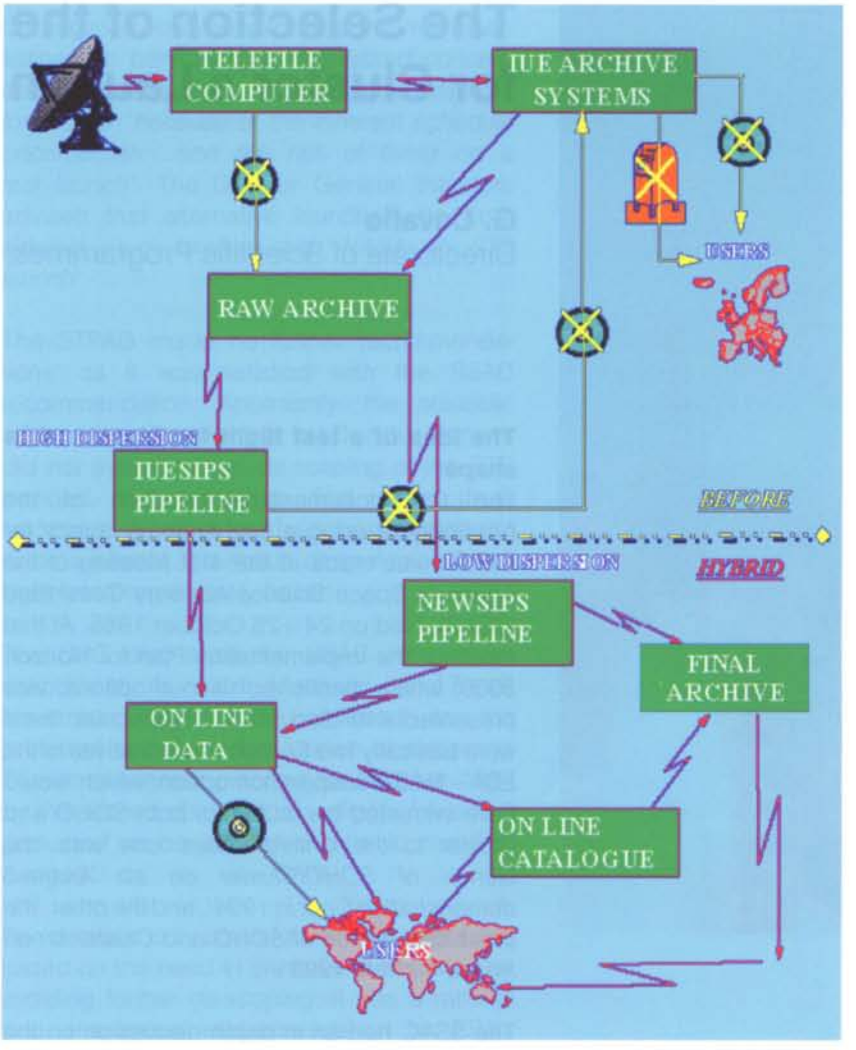

Figure 3. Internal data reduction and delivery within the IUE project, showing the major changes implemented to support the 'hybrid' operations. The schematic above the dashed yellow line represents the situation as it was in the past (data flow indicated by yellow arrows), and that below the line the currently implemented system. The red flashes indicate automatic data and information flow, without human intervention

This re-engineering of the data-handling subsystem started during the spring of 1995, and in late October we were able to deliver IUE data to the scientists of the 19th Episode and the astronomical user community as a whole, in Europe and the USA. In the five months since the start of 'hybrid' operations on 1 October 1995, more than 700 spectral files (19th Episode data) have been retrieved from the distribution node by more than 50 different scientists at external institutes.

During almost 20 years of operations, the IUE project has evolved in ways which could not have been anticipated at the time of the satellite's launch in 1978. As a consequence, it supplies support arrangements comparable to many other space projects of more recent vintage. In the 'hybrid' operations phase, IUE has become the only satellite capable of delivering processed science observations to the user community within 48 h, without restriction.

The Selection of the Ariane-5 Test Flight for Cluster's Launch

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The idea of a test flight for Cluster takes shape

The first documentable mention of the possibility of using a free Ariane-5 launch for Cluster was made at the 41st Meeting of the Agency's Space Science Advisory Committee (SSAC), held on 24 – 25 October 1985. At that meeting, the Implementation Plan for Horizon 2000, which mentioned various options, was presented and discussed. In particular, there were basically two European alternatives to the ESA – NASA cooperation option, which would have entrusted the launch of both SOHO and Cluster to the United States: one was *'the launch of SOHO/Cluster on an Ariane-5 demonstration flight in 1994'*, and the other *'the combined launch of SOHO and Cluster on an Ariane-4 in late 1993'*.

The SSAC had an in-depth discussion on the two Solar Terrestrial Physics Cornerstone missions, and three possibilities were noted:

(i) SOHO launched by the Shuttle, Cluster by Ariane.
(ii) flight of both projects on Ariane-4; however, the costs would probably be in excess of 400 MAU
(iii) *'A free demonstration flight on Ariane-5 should therefore be considered for flight of the European STP'*.

The SSAC Recommendation on the Implementation Plan for Space Science: Horizon 2000 did not go into the details of the various launch options, probably because the issue was not yet considered mature.

Two important facts appear from this first document:

- There were other missions wishing to be launched on an Ariane-5 demonstration flight.
- In the minds of the early planners, a single Ariane-4 could be sufficient to put both SOHO and Cluster into orbit. The situation was evolving quickly, however, in the direction of a more complex and heavier mission.

The decision

The cost issue for the STP Cornerstone was felt so deeply at the time that a special meeting of the SSAC was called on 19 November 1985. The costs resulting from the internal analysis and an industrial study exceeded the ceiling set by the Implementation Plan of 400 MAU (Million Accounting Units) at 1985 economic conditions. Roughly speaking, the overall cost of STP, including two launches, was in excess of 700 MAU. According to the Executive, the Cornerstone could cost 560 MAU, on the assumption of de-scoping both missions and having both launched by NASA. The cost would increase to 650 MAU if both (de-scoped) missions were launched on a single Ariane-4. On the other hand, the costs associated with a free Ariane-5 launch were expected to be of the order of 20 MAU.

The situation was considered to be so difficult that the proposal was made to launch only one of the two missions as the first Cornerstone. If this view had been accepted, SOHO and Cluster would have been put into competition against each other. It was therefore discarded because of the recognised synergy between SOHO and Cluster. In the end, the SSAC advised the Executive to adopt the philosophy of starting on a de-scoped SOHO and a three-spacecraft Cluster mission, whilst being ready to up-scope both missions if other solutions could be found. The SSAC asked the Executive to convene the Science Working Teams of both missions as soon as possible.

The Solar System Working Group (SSWG) met on 9 January 1986 and the SSAC held its 43rd Meeting the following day. The SSAC formulated a recommendation on the selection of the next scientific project, in which it manifested its agreement with the recommendations of the SSWG, *'in particular that an STP Advisory Group (STPAG) be set up as soon as possible, whose principal task would be to work closely with the Executive on ways and means to achieve the necessary cost reductions'*.

The terms of reference were broad (*'to advise on ways of ensuring that the programme complies with the financial boundary conditions established by the SPC, without diluting the scientific validity of the Cornerstone'*), and the Executive was asked to provide equally broad support.

The STPAG was immediately convened under the chairmanship of Prof. D. Southwood (Imperial College London), and held four meetings, on 23 April, on 23 – 24 June, on 17 – 18 September and on 3 December 1986, respectively. At the third of these meetings three options were presented, which were the result of the evolution of previous proposals.

In the end, the STPAG strongly recommended to the Director of Scientific Programmes that he investigate all possible means to implement 'Option B', which would afford greater autonomy to ESA, as the STP Cornerstone. According to 'Option B', ESA would provide the SOHO spacecraft and four Cluster spacecraft. One of the Cluster spacecraft would have a dual-orbit capability and first perform an equatorial mission. NASA would operate the initial equatorial mission as well as SOHO, and would take the Cluster wide-band link data. Later ESA would operate the four Cluster spacecraft. NASA would launch the spacecraft designed to perform the dual-orbit mission and SOHO. The launch of the remaining Cluster spacecraft on an Ariane-5 test flight was being investigated.

The third STPAG Meeting was followed by the 45th SSAC Meeting (in Innsbruck, 8 October 1986). Here the SSAC produced its 'Recommendation on the Implementation of the STP Cornerstone', having heard both the previous reports of the STPAG and the opinion of the SSWG. The so-called 'Option-B' was recommended, according to which ESA would *'develop four identical Cluster spacecraft, one of which will be launched by NASA in 1993 into an equatorial orbit.....ESA expects to launch the other three Cluster spacecraft in 1994 on an Ariane-5 demonstration flight'*. The text goes on to say that *'The SSAC unanimously and strongly recommends that the scenario be followed with determination by the Executive and that a confirmation of NASA's commitment be sought with urgency'*.

At the fourth and last STPAG Meeting (on 3 December 1986), a report was given of a meeting on 8 October between ESA's Director General at the time (Prof. R. Lüst) and the Director of Scientific Programmes on the subject of Cluster. It was clear that the Director General was keen to maintain the STP Cornerstone, but he expressed some reservations. In particular, he *'expressed concern about the planned use of the Ariane-5 test flight for Cluster, because of the inherent schedule uncertainties.....and the risk of flying on a test launch'*. The Director General therefore advised that alternative launchers be considered, *'e.g. explore with NASA an STS launch'*.

The STPAG made no further recommendations, as it was satisfied with the SSAC recommendation. Apparently, the scientific advisory structure felt that the Director General did not advise further de-scoping of the STP payload, but rather to find other (free) launchers. As other free launchers proved not to be available, the notion of an Ariane-5 test flight was progressively frozen.

The SPC discussed the SSAC recommendations at its 43rd Meeting on 17 – 18 November 1986 and confirmed as the preferred approach the *'launch of remaining Cluster spacecraft planned for October 1994 by the second demonstration flight of Ariane-5 (assumed to be without charge to the STP budget)'*.

The decision to fly on an Ariane-5 test flight was based on the need to preserve the mission by avoiding further de-scoping. It was a rational and unanimous recommendation by ESA's scientific advisory structure. At that time, a single Ariane-4 could not put the four Cluster satellites into orbit.

The political importance of Ariane-5 must have been felt to be a reassuring element. On the other hand, the fact that space is a risky business was well-known: by October 1986 there had been 18 Ariane launches, 4 of them unsuccessful; the Shuttle disaster was still a recent memory. We might add that even the Ariane-4's excellent launch record to date equates to a reliability of about 96% (4 failures out of 64 launches).

There were other competitors hoping to be launched on an Ariane-5 test flight, from both within and outside the Agency. In the following years, the SPC would express its worry that other customers might secure the free flight in place of Cluster.

The follow-up

The first action was the release of the Announcement of Opportunity (AO) for the payload on 1 March 1987. Consistent with the above decisions, the AO stated that the launch vehicle would be an Ariane-5 (flight no. 2). The Principal Investigators, in submitting their

responses to the AO, accepted this choice and launch on an Ariane-5 test flight was never questioned during the Science Working Team meetings (the SWT included a number of scientists who participated in the original decision).

By the time of the 48th SPC Meeting in July 1988, there was again *'increasing concern over potential financial-resource needs'*. In the meantime, a further Programme Review had been conducted by a small ad-hoc review team, chaired by Prof. H. Balsiger (Univ. of Bern), which made a number of recommendations.

The Balsiger Committee had held two meetings, on 13 – 14 January and 15 February 1988. As a cost-reducing measure, it examined the possibility of having NASA launch Cluster (as the Director General had originally suggested). However, no satisfactory technical solution was found. A final decision on the launcher needed to be taken by the end of 1988 at the latest.

However, already at the time of the 48th SPC Meeting, it was generally accepted that the Cluster mission would consist of four spinning spacecraft, ready to be launched by Ariane-5 in December 1995. The Ariane-5 opportunity, however, implied some *'non-optimum injection strategy for the Cluster mission, which had to be compensated for within the spacecraft design'*. Furthermore, some charges, partly known and partly as yet undefined in 1988, would be levied.

Clearly, the advantage of having a free launch was considered to far outweigh the disadvantages listed above, in the eyes of the advisory structure and of the SPC itself which, at its 48th Meeting, approved the course of action proposed by the Executive, including the Ariane-5 launch, without further mention of the risk connected with such a test flight.

No doubts regarding Ariane-5 were raised at subsequent SPC meetings. At the 49th Meeting in August 1988, the Executive noted that *'it was still planned to launch Cluster on the first or second Ariane-5 demonstration flight, while SOHO remained on the US Shuttle manifest, although SOHO's compatibility with a conventional launcher would be maintained for as long as this was not ruled out by financial considerations'*.

The minutes of the 49th SSAC Meeting on 7 November 1988 mention a 'new cost at completion of 482 MAU at 1984 prices, compared with the 460 MAU envelope allocated by the SPC. The Balsiger Committee had reduced the cost and also the risk of subsequent cost escalation. Since the figure of 482 MAU was within 5% of the goal, the Director General had accepted that the project should continue, but that it should be aimed to reduce the cost, bringing it back to the 460 MAU figure'. Furthermore, *'the SPC had taken note and concurred with the course of action proposed by the Executive'*.

A Call for Experiments to fly on the Ariane-5 development launch in 1995 had been issued in early 1990, and the intention was to select the passengers by end-1990/early-1991. Ten proposals had been received. The Call created concern among the SPC Delegations, who feared that other spacecraft might be launched free rather than Cluster. However, at its 54th Meeting on 31 May 1990, the SPC was informed that *'the Director of Space Transportation Systems had given assurance that the interests of the Science Programme would be safeguarded when it came to selecting APEX passengers'*.

At the same meeting, the Executive informed the Delegations that, *'although Ariane flight 501 was scheduled for April 1995 and flight 502 for October 1995, those responsible for the Ariane-5 Programme were fully aware that Cluster would not be ready for launch until December 1995, and were now working to that timescale'*.

In the meantime, work was continuing with Ariane to define the Cluster launch-vehicle interfaces.

A discussion about the possible insurance of scientific satellites had taken place at the 53rd SPC Meeting (20 – 21 November 1989) in the light of the failure of the Apogee Boost Motor on Hipparcos. According to the Executive, insurance should be discussed on a case-by-case basis. Self-insurance was out of the question, because it simply meant that the ESA Member States would have to commit to provide the money for a replacement satellite. NASA's scientific satellites, it was noted, were not insured. The matter was left for further consideration. However, the almost miraculous recovery of the Hipparcos mission truncated all further discussion of insurance at that point.

From Ariane-502 to Ariane-501

At the 56th SPC Meeting (12 – 13 June 1990), Delegations were *'advised by the Executive that Ariane-5 Project Managers were fully aware of the requirements for Cluster. An APEX flight was still being negotiated'*.

At the 60th SPC Meeting (12 – 13 June 1991), the Executive confirmed that *'agreement in principle had been reached on the launch configuration for Cluster, using Ariane-5. It explained to Delegations that its preference for Cluster, which would be ready for launch as from December 1995, would be to use Flight 501, in case the flight were delayed, which would make the schedules compatible'.*

Delegations did not express any preference for either Ariane-501 or Ariane-502. The important issue was still to make sure that Cluster had a free launch, compatible with its development schedule.

A report was presented at the 61st SPC Meeting (6 – 7 November 1991) on the situation with regard to the negotiations to fly Cluster on APEX. At that point, Cluster was still on Ariane-502. It would be launched together with Amsat, which had just been selected for the launch.

A further report was presented at the 64th SPC Meeting (4 – 5 June 1992), according to which Cluster was still on Ariane-502, scheduled for April 1996. A few months later, at the 65th SPC Meeting (3 – 4 November 1992), a new report stated that *'A detailed review of the APEX programme has recently taken place to consolidate the launch configurations for V501 and V502 in view of the reduced Ariane support programme. Both launches will now use the short fairing and Speltra, and will have a total capacity of 5200 kg. Cluster is currently compatible with both launch configurations. During the review, APEX confirmed that the Cluster schedule was compatible with the V501 schedule'.* The document carries the date of 16 October 1992, but a major decision was being taken precisely at that time.

Following an APEX/Artemis/Cluster meeting at ESTEC on 8 October 1992, a passenger review report was issued on 21 October 1992 recommending Cluster's flight on Ariane-501. The main reason given by the review was that *'Cluster will be ready before Artemis and matches the Ariane-501 date more closely'.* Besides, putting Artemis on Ariane-502 would *'offer additional time to find a co-passenger'.*

On 11 – 12 December 1992, ESA's Directors of Science and Space Transportation agreed to the above recommendation, to *'assign Cluster to Ariane-501'.*

The Ariane Programme Board had been officially informed of the re-assignment in a document, with the following words: *'A review of the requirements and constraints of Cluster and Artemis, and their development timetables, has resulted in the following re-assignment of passengers:*

- *Cluster (4 satellites) will be the only passenger on Ariane-501 (previously it was to have been flown on Ariane-502 with Amsat)*
- *Artemis will fly on Ariane-502 with Amsat (previously it was to fly on A501 without Amsat). A third passenger still has to be found'.*

Thus the shift to flight 501 was driven mainly by schedule and flight-opportunity considerations. No specific announcement was made to the SPC, although the shift had long been in the air. The situation was subsequently regularly reported in the SPC documents, but no special mention was made it at SPC meetings.

The SSAC and Cluster Science Working Team were also informed of the final assignment of Cluster to Ariane-501. Neither the Principal Investigators involved, nor the advisory structure, ever objected. In fact, some PI's were happier with a launch on the first flight, because they felt that an enormous effort would go into making it a success. It was felt that the chances of a failure occurring on either the first or the second flight of an Ariane-5 rocket were even, as the second flight of Ariane-1 and the first flight of Ariane-2 had failed. Moreover, the fact that Ariane-5 had been designed for manned spaceflight seemed to offer an even higher probability of success rather than using another launcher, even one with a low failure rate.

It is noteworthy that NASA launched the first Space Shuttle in April 1980 with astronauts on board, and ISAS of Japan still plans to launch its prestigious MUSES-C mission on the maiden flight of their new M-V launcher in September 1996, despite the Ariane-5 experience.

Conclusion

All in all then, there was nothing so extraordinary about the ESA decision to fly the Cluster mission on Ariane-501, especially given the great emphasis on cost savings to which the mission was subjected throughout its development. Of course, with the luxury of twenty-twenty hindsight, we all might have taken different decisions along the way.

The above review of the processes and considerations affecting the decisions *at the times that they had to be taken*, shows that the decision to fly on the first Ariane-5 flight was logically well founded as well as financially attractive.

The International Space Science Institute (ISSI)

Opportunities for International Research Teams
Call for Proposals

ISSI, in Bern Switzerland, offers a unique scientific environment, the possibility of contact and interaction with leading international experts in space physics, access to databases, computing and office facilities, and financial support if needed.

Proposals are invited from teams of two or more scientists from different institutions for projects lasting up to several months (continuous or interrupted). Applicants, of PhD level, are expected to make a firm commitment to spend the requisite period at ISSI.

Selection: Proposals will be judged on the scientific significance of the proposed research and applicants' track records, as well as compatibility with the scientific aims of ISSI and the availability of the necessary support. Adequate representation of ESA Member States will constitute a positive element.

Funding: Participants are asked where possible to find their own funds. However, ISSI can provide a mixed funding option, whereby applicants receive both a basic salary and return travel costs from home, and ISSI contributes all or part of the living costs.

Applications: Applications (maximum 5 pages) should include: the scientific rationale, schedule of the project, facilities required (computers, database access, etc.), financial requirements, and the basis for choosing ISSI as the host, list of participants with appended brief CVs, statement on financial backing, and address, fax and phone numbers and e-mail address.

Applications should be sent, by the leading investigator, to:

ISSI, Hallerstrasse 6, CH-3012 Bern, Switzerland

to arrive no later than **30 September 1996**.

Further information is available via the ISSI Home Page:

http://ubeclu.unibe.ch/issi/index.html.

A detailed description of ISSI and its activities was also published in ESA Bulletin No. 86 (May 1996).

Any questions arising should be addressed to Dr Vittorio Manno at ISSI:

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The Cluster Mission Planning Concept

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The mission-planning environment described here is that established for the original baseline Cluster mission. However, the flexibility of its tools and procedures allows it to be easily applied to serve the mission-recovery options currently under investigation following the Ariane-5 launcher failure in June (see ESA Bulletin No. 86, page 99). In particular, the flight of the already approved 'Phoenix' spacecraft (a fifth Cluster), possibly followed by the addition of new spacecraft at a later date, can be handled by making configuration changes and without requiring major modifications to the overall system. The experience gained and the concepts and tools developed for Cluster are also readily adaptable for supporting other future scientific missions.

Introduction

In the original Cluster baseline mission, the four identical Cluster spacecraft were to be flown in formation in highly elliptical orbits (about 25 000 km perigee, 123 000 km apogee), with an inclination close to 90° and a line of apsides close to the equatorial plane. Two ground stations located in Europe – Redu in Belgium and Odenwald in Germany – were to be dedicated to the Cluster mission, giving each spacecraft an average coverage period of about 25% of the total mission time.

The goal of the mission was to make scientific measurements over at least half of the period spent by the spacecraft above 35 000 km (the typical height below which some instruments have to be switched off due to high radiation levels). Measurements were to be taken in low-bit-rate (normal) and high-bit-rate (burst) modes. Since the available on-board storage could not support long periods in burst mode, careful scientific planning was required to select the best measurement periods and modes. The operations of the entire Cluster payload, consisting of eleven instruments on each of the four spacecraft, also had to be coordinated to achieve the optimum scientific output in the selected regions of the magnetosphere in which measurements were to be collected.

Responsibility for distilling the scientific operations requests for the different instruments into a single, coordinated and agreed input lay with the Science Working Team (SWT), supported by the Joint Science Operations Centre (JSOC), located at the Rutherford Appleton Laboratories (RAL) in Didcot (UK). The subsequent planning of all spacecraft and ground-segment activities based on the SWT's input was the responsibility of the Cluster Mission Planning System (CMPS) at ESOC.

The purpose of a mission planning system

In general, the purpose of a space mission planning system (Fig. 1) is to ensure that the mission operations are scheduled at the Operations Control Centre (OCC) in such a way that the needs of the users are satisfied within the scope, resources and constraints of the mission. The scheduling is based on a plan, normally divided into cyclic planning periods, which is constructed by merging the users' inputs with the mission-specific scheduling rules and constraints. From this plan, a set of command schedules for the spacecraft and the ground stations is then derived.

The inputs to the plan can include the science operations requests, coming from the users; the spacecraft operations requests generated at the OCC, taking into account all other spacecraft and ground-segment routine maintenance operations; the flight-dynamics events (visibility periods, eclipses, etc.); and a set of rules and constraints (profile of the resources, list of incompatible requests, capabilities of the spacecraft and ground segment, data-link capacities, etc.). The planning period can be for the entire mission or just a part of it. For Cluster, a planning period of three orbits, or about seven days, has been chosen for practical reasons, since this allows a one-week periodicity for all planning activities.

The mission planning system uses all of the above inputs to find windows responding to selected criteria (e.g. when sunlight and perigee occur at the same time) in order to identify the different scheduling possibilities for meeting the given plan. It can then propose one or more possible schedules using an automatic scheduler; a simpler alternative is to provide the tools with which to build a schedule manually. The final output is translated into a list

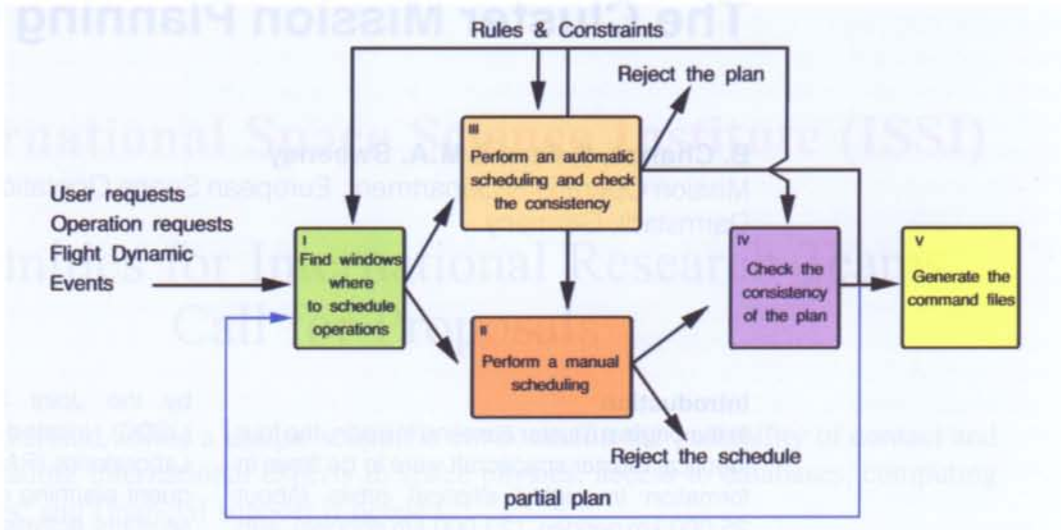


Figure 1. Principles of a mission-planning system

of command sequences to be executed by the spacecraft and possibly, as in the case of Cluster, also by the ground stations.

In summary then, the three major steps of the mission-planning activity are to:

- find windows responding to criteria where operations can be scheduled
- build a schedule compatible with the mission rules and constraints
- generate the final detailed command files.

The challenge of the Cluster mission planning

In the case of Cluster, the complexity of the mission and the limited resources available for the routine operations phase required the use of a sophisticated planning system for the scheduling of all the science operations of the four spacecraft. In particular, due to the strict interrelations between the various instruments forming the Cluster payload, the science operations called for a high level of coordination between the Principal Investigators well in advance of the actual execution of the operations. In addition, the need to execute identical parallel activities on all four spacecraft, the onboard data-storage constraints, and the limitation of having only two ground stations in the northern hemisphere for data recovery and spacecraft control, made very careful deployment of resources an absolute necessity.

To support the coordination activities, a Joint Science Operations Centre (JSOC) was established, providing support to the Science Working Team (SWT) responsible for all scientific decisions associated with Cluster mission operations. During the mission, the JSOC was to interface on the one side with the SWT, to receive the overall guidelines for the generation of science operations requests, and with the PIs to acquire detailed information on the related instrument operating modes, and on the other side with ESOC, to which it would regularly send a merged set of science operations requests for use by the OCC as input to the mission planning system.

The mission planning activities at ESOC are supported by a number of software tools, centred around the Cluster Mission Planning System (CMPS), designed to handle the analysis of the science operations requests, the merging of those requests with the other spacecraft operations necessary during the routine phase of the mission, and the definition of a unique mission plan. The CMPS would schedule all activities related to the onboard storage of data and its transmission to ground. In particular, it would decide which parts of the actual visibility period over each ground station would be assigned to each of the four spacecraft, trying to select the strategy most likely to satisfy the science operations requests without violating any of the mission constraints.

The final result of these planning activities is a set of control files which would automatically drive the synchronised operations of all four spacecraft and the two ground stations. These files would be transferred to the relevant computer systems at the OCC, which would handle the real-time control and operations.

Evolution of the mission-planning concept

The mission planning system for Cluster was defined at the end of 1992, about three years before the original launch date. The additional complexity of the Cluster requirements compared with those for previous missions lay in the fact that, given a particular set of science operations requests (which implies a certain data-acquisition profile), there are a large number of possible solutions to the problem of recovering all of the data from all four spacecraft (by using the onboard tape recorders and downloading the data later, by transmitting the data immediately via the direct links, or a combination of the two). Many of them, however, would violate the system constraints.

To optimise the science data flow first from the spacecraft to the control centre and then to the users, a special Cluster Data Resources Analysis Tool (CDRAT) was commissioned. Delays in its subsequent development meant, however, that this approach had to be abandoned. Once the CDRAT did eventually become available, it was used extensively to test and refine the scheduling algorithm that had been implemented in the CMPS in the meantime. The choice had been based on the fundamental assumption that the onboard resources were the limiting factor, rather than the ground resources. This was true until the Cluster spacecraft design was upgraded by replacing the small 1 Gbit tape recorder with two 2.25 Gbit solid-state recorders, which could also be used in sequence. This multiplied the onboard storage capacity of each spacecraft by a factor of 4.5, shifting the limiting resource constraints from the onboard storage to the data-link capacity from the ground stations to the OCC and the processing speed of the computers involved in digesting this enormous amount of data.

The CDRAT tool was also inserted into the planning cycle at the point where the Master Science Plan for one year of operations was to be produced by the SWT, in order to identify data-flow resource conflicts at an early stage.

A final refinement in the system was the generation of a parallel tool which would use the results of the CMPS detailed planning to produce auxiliary information for conducting the real-time operations (so-called SPACON timeline).

The CMPS has therefore become a comprehensive set of tools which work together at different planning levels, from the initial long-term baseline planning to the final operational level in which the detailed commands and instructions are generated.

Overview of the CMPS responsibilities

The control of the four Cluster spacecraft was to be based on the use of a single control centre in conjunction with two ground stations, each of which would normally acquire a pair of spacecraft. Because the spacecraft would fly relatively close together (several hundred to several thousand kilometres apart), their visibility periods from Earth would be almost identical and actual contact time with the station had therefore to be shared. The four spacecraft were to be controlled mainly via time-tagged commands, whilst the stations would be unmanned and remotely controlled from the OCC at ESOC, also via automatic scheduling.

The orbital period of the spacecraft would have been approximately 57 h, with two or three visibility periods lasting 10 – 20 h. In principle, scientific measurements could take place over any part of the orbit, independently of the actual ground contact time. The onboard recorders would have allowed full coverage of the orbit at low bit rate, or up to 8 h of continuous recording in high-bit-rate mode. Most of the measurements were to have been executed simultaneously by the four spacecraft. This means that the recorders of at least two spacecraft would have had to be used even during ground coverage, while the other two spacecraft downlinked their data directly to the stations in real-time. The contact period with the ground stations would mainly have been used to dump the data stored on the recorders during the long non-coverage periods. This operational approach required a special algorithm (Fig. 2) to allocate the contact time for each spacecraft over the available ground stations, based on the actual use of the onboard recorders, the particular scientific measurements requested, and the overall coverage time available.

The CMPS is a fully automated system that derives and proposes a schedule to the planning engineer. The system gives the latter the ability to influence the results of the scheduling process by modifying the values of configurable parameters and by formulating special operations requests.

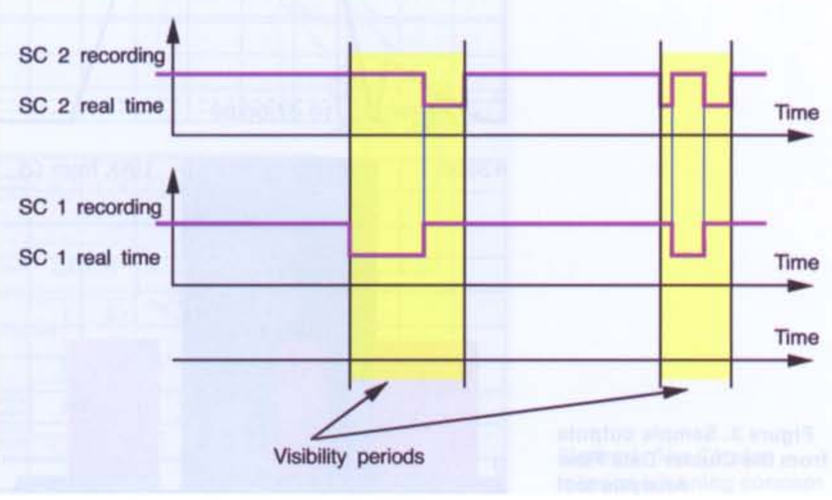


Figure 2. Handling of visibility periods by the scheduling algorithm

Specific tasks that can be handled by the CMPS include:
- management of on-board power
- management of the on-board time-tagged command buffer
- management of on-board data generation, storage and dumping to the ground
- checking the usage of on-board resources (data storage, power, time-tagged command buffer)
- selection of the telemetry and data acquisition mode
- selection of the ground contact periods for each spacecraft
- switching of the on-board antennas
- control of all routine ground-station operations.

The most critical element in the CMPS is the algorithm that determines the telemetry and data acquisition mode timeline, from which the management of the on-board data generation and storage, and the definition of the ground contacts and recorder dumping periods are derived. This algorithm has to maximise the scientific return whilst respecting the prevailing operational constraints.

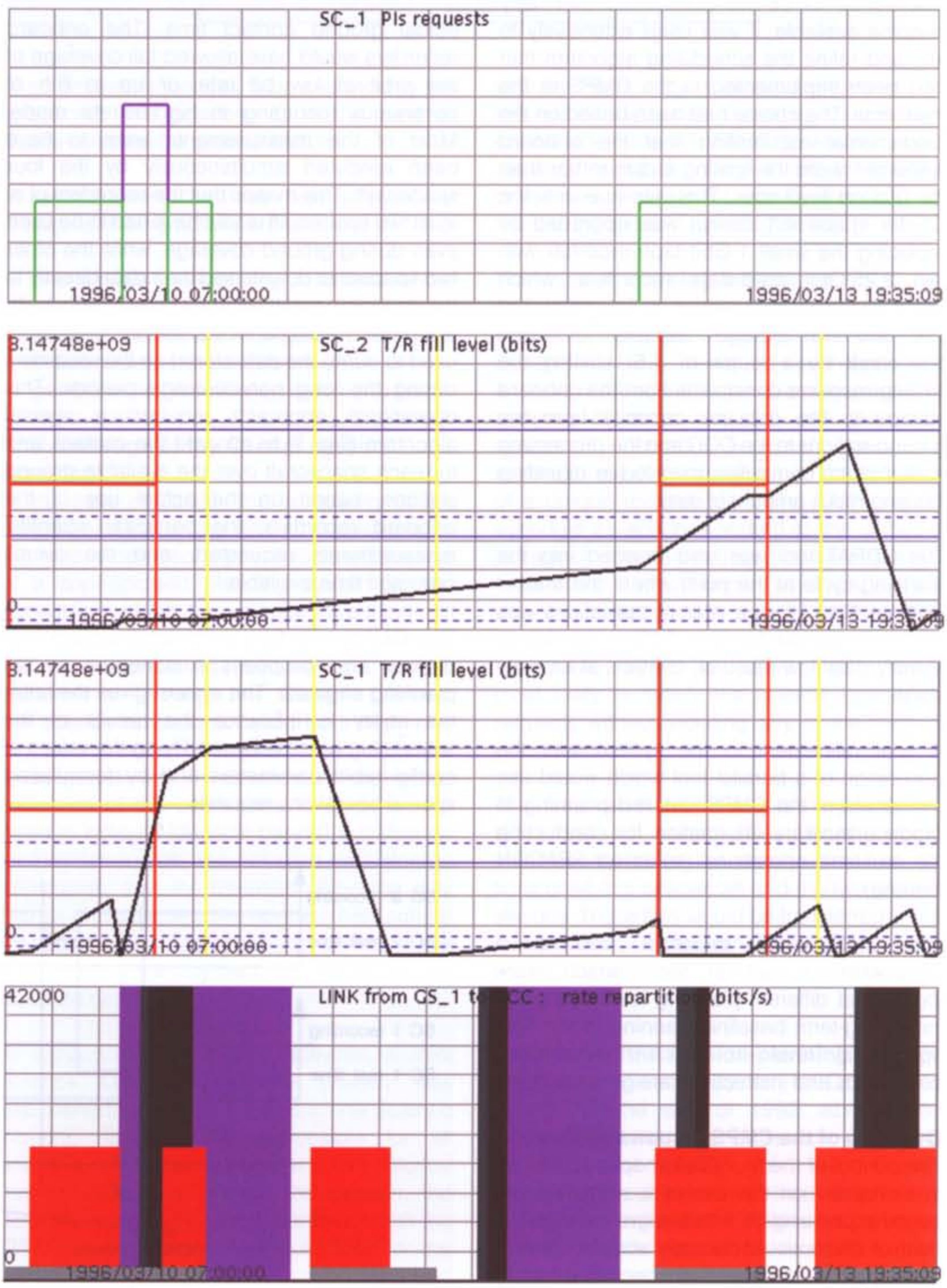


Figure 3. Sample outputs from the Cluster Data Flow Analysis tool

Use of the Cluster data-flow simulator

The second major tool developed at ESOC for the Cluster planning activities is the CDRAT, originally conceived as a data-flow simulator for the mission-analysis phase, but now fully integrated into the medium- and long-term mission planning activities.

The CDRAT simulates the data flow from the spacecraft through the ground station up until its arrival at the Operations Control Centre (ESOC). It provides such statistics as the time spent by each data package in the various stages of the flow. The CDRAT also provides the ability to experiment with the parameters of the simulation to determine their impact on the overall system, or to compare different strategies under the same initial conditions (Fig. 3).

Another area in which the CDRAT was used for the Cluster baseline mission was to identify basic rules and guidelines for use by the SWT in defining the initial Master Science Plan, which could already take into account the overall data acquisition constraints and thereby minimise the chances of the related science operations requests being rejected.

The Cluster mission planning cycles and activities

The planning environment

The key players in the Cluster-mission planning process have been the experiment Principal Investigators (PIs), the JSOC personnel as the operational arm of the SWT, and the OCC at ESOC (Fig. 4).

The initiators of the process were to be the PIs, each of these eleven scientists being responsible for one of the instruments carried by each spacecraft. At the same time, they were also to be the final recipients of the mission products from the four satellites. As part of the SWT, which includes all Principal and Co-Investigators for the Cluster mission, a Science Operations Working Group (SOWG) was established, to which all PIs and representatives of JSOC, ESOC and the Project Scientist belong. The SOWG was to meet regularly, every two to three months, being charged with creating the baseline plan for the mission, called the Master Science Plan (MSP). The latter was to lay down the periods of measurement and the main experiment modes for periods of between six and twelve months ahead.

The JSOC would be responsible for collecting the PI's detailed requests for each planning period and merging them into a coordinated input to ESOC. Additional services to be provided by the JSOC to the Cluster PIs and to the science community in general included the provision of orbit information, selected science telemetry monitoring, etc.

The OCC at ESOC was to have overall responsibility for the Cluster mission operations, and therefore played a central role in the mission-planning activities. The feasibility of the Master Science Plan would also be analysed at ESOC before being finally approved by the Project Scientist and released to JSOC as the official baseline mission plan. The mission planners at ESOC, who form part of the Cluster

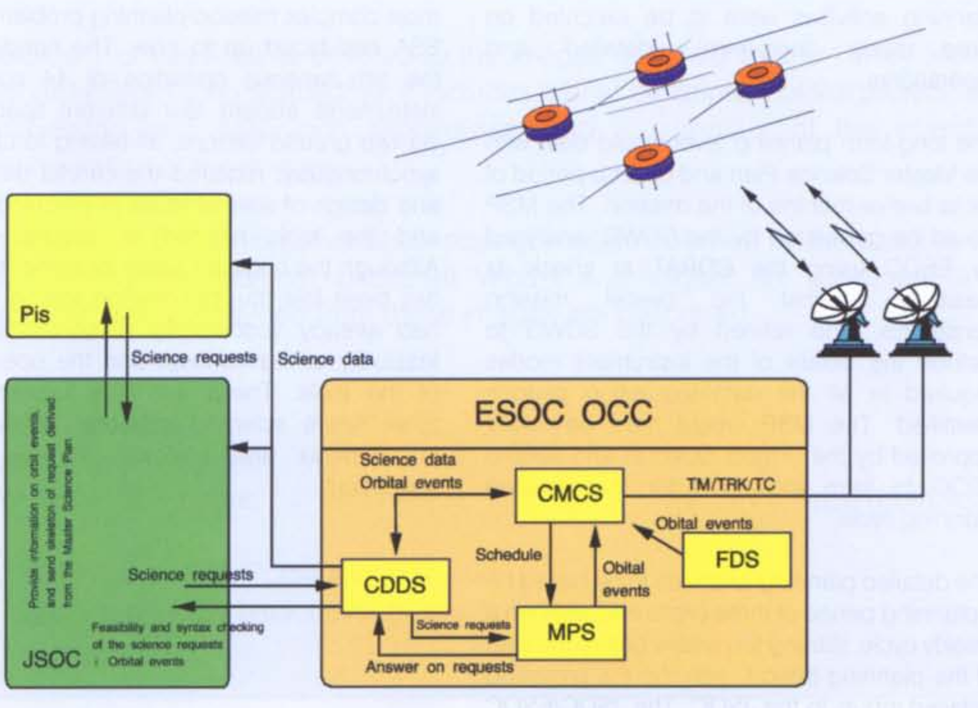


Figure 4. The Cluster mission-planning concept

Flight Control Team, would be responsible for merging the science operations requests received from JSOC with the other mission-related operations to form an integrated schedule of space- and ground-segment activities.

As shown in Figure 4, within ESOC the CMPS would be in charge of the mission planning activities and is connected to the CMCS (Cluster Mission Control System), the CDDS (Cluster Data Disposition System), and the FDS (Flight Dynamics System). The CMCS is responsible for both the real-time and off-line processing of the telemetry and for spacecraft control via telecommanding. It receives from the CMPS the Detailed Schedule Files which contain the time-tagged command sequences to be uplinked to the spacecraft, and the schedules to be transferred to the station computers responsible for monitoring and controlling the ground stations. The FDS produces the spacecraft-related orbit and attitude information. Both JSOC and the CMPS at ESOC receive and utilise part of this information. Finally, the CDDS is the interfacing computer system between ESOC and the rest of the world (except for the ground stations, which interface with the CMCS). This system was to have provided the Cluster PIs with near-real-time access to the science data, produce daily a set of CD-ROMs carrying all of the mission data for the Cluster science community, and perform the file exchange between ESOC and JSOC.

The planning cycles and the JSOC/ESOC interface

As mentioned above, the Cluster-mission planning activities were to be executed on three levels: 'long-term', 'detailed' and 'operational'.

The long-term planning level would deal with the Master Science Plan and cover a period of six to twelve months of the mission. The MSP would be generated by the SOWG, analysed by ESOC using the CDRAT to check its feasibility against the overall mission constraints, and refined by the SOWG to include the details of the instrument modes required in all the data-acquisition periods identified. The MSP would then be finally approved by the Project Scientist and sent to JSOC to form the basis for the detailed planning cycle.

The detailed planning level was to be based on a planning period of three orbits and work on a weekly cycle, starting ten weeks before the start of the planning period, with the PIs providing detailed inputs to the JSOC. The JSOC/ESOC interface was to be active at this level, starting about six weeks before the start of the planning period. It involved the transfer of planning information files in both directions between the two centres. Files passed from JSOC to ESOC were to include so-called 'Observation Request Files', containing the operations required for the correct functioning of the payload instruments, primarily during science data acquisition periods but also related to instrument safety operations, e.g. during perigee passes. The Observation Requests would be constructed by JSOC taking into account the finalised MSP and the refinement or modification requests received from the individual PIs.

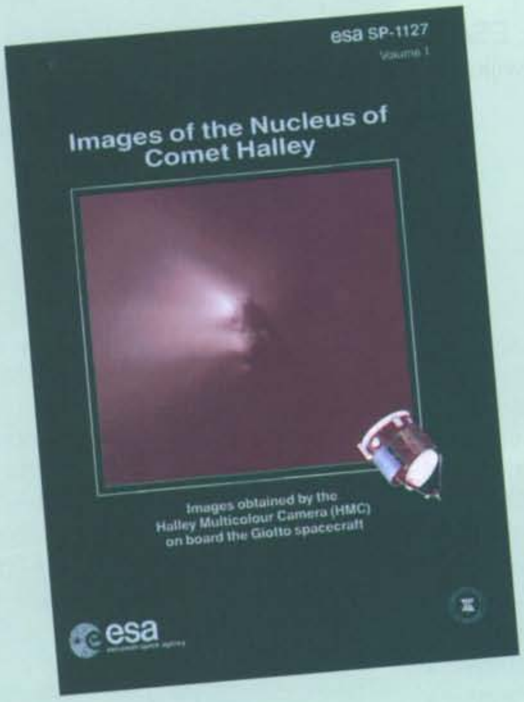
The detailed planning was to be an iterative process with information originating from the scientists being passed to JSOC and then on to ESOC. Any problems arising would be highlighted and sent back electronically to JSOC for action, with the possible need for further dialogue with the scientists. This cycle was to be repeated until a viable plan of operations was arrived at.

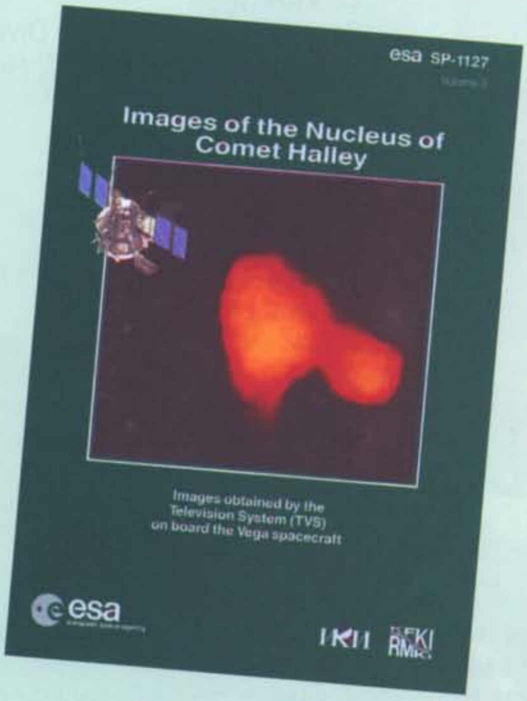
The final stage of the planning activities would be at the operational level, where the consolidated plans are translated on a daily basis into actual operations schedules and implemented by the spacecraft-control personnel. It is here that the CMPS was to be used to generate the detailed schedules for both the spacecraft and the ground stations.

Conclusion

The planning of the routine phases of the Cluster mission probably represents one of the most complex mission-planning problems that ESA has faced up to now. The handling of the simultaneous operation of 44 scientific instruments aboard four different spacecraft via two ground stations, all having to operate synchronously, required the careful definition and design of several levels of planning cycle and the tools needed to support them. Although the original Cluster baseline mission has been lost, the pre-mission testing phase had already successfully demonstrated the feasibility of the concept and the operability of the tools. These are now available for other future scientific missions, as well as for 'Phoenix' and, hopefully, its new sister spacecraft.

Atlas of Images of the Nucleus of Comet Halley





Apparitions of Comet Halley have been recorded regularly in history since 240 BC, but it was not until its 1066 AD apparition that it was first depicted visually, and then only in a very stylistic manner. The first accurate scientific drawing of Comet Halley was made in 1682 by Hevelius. Further drawings with increasing detail were made during the 1759 and 1835 apparitions, and the first photographic plates were made during Halley's return in 1910. By the time Halley next returned in 1985/6, space flights to comets were possible and it was met by an armada of five spacecraft, three of which – Giotto, Vega-1 and Vega-2 – carried high-resolution cameras. These images revealed the existence of a cometary nucleus for the first time.

Volume 1 of this Atlas is devoted to the images obtained by the Halley Multicolour Camera (HMC) aboard ESA's Giotto spacecraft. It includes a brief description of the project, an account of the image processing and calibration procedures, and a summary of the scientific results to facilitate interpretation of the images.

In Volume 2, the consecutive sequences of images obtained by the imaging experiments aboard the Russian-led Intercosmos spacecraft Vega-1 and Vega-2 are presented and the most important scientific results obtained from these images are described.

ESA SP-1127
Volume 1: 252 pages
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The Challenge of the EuroMir 95 Technology Experiments

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Microbiological sampling techniques, earth-radiation-environment monitoring, gas-contaminant bio-filtering tools, multimedia communications technology, passive magnetic-levitation techniques for fluid-dynamics study, robotics-technology development, gas-sensor systems and analysis tools for human kinematics in microgravity – all were a part of the truly multidisciplinary Technology Experiments package flown aboard the record-breaking EuroMir 95 mission. Final processing and evaluation of the vast amount of data gathered from the experiments will not be completed until the end of the year – work is currently in progress at nine different centres throughout Europe – and this article therefore provides but a first glimpse of the mission's many findings and their implications for long-term manned spaceflight in the context of the International Space Station.

The experiments flown

MIRIAM-T2

This contamination monitoring experiment was designed to investigate microbial and fungine growth onboard a space station in long-term orbit. A particular objective was to verify two quick and simple methods for detecting and evaluating the microbial contamination. The first used a semi-automatic, quasi-real-time monitoring system known as a 'luminometer' which exploits the so-called 'bioluminescence reaction mechanism' (microbial biomass quantitative evaluation with adenosine triphosphate, or ATP, which is the major source of energy for cellular reactions). The second was based on the usual colony-forming-unit (CFU) method, but the samples were cultured directly on the sampling membranes using a simple 'mini-culture' technique.

The latter uses sterile carbon paper discs, embedded with nutrient, contained in transparent holders. Sampled membranes could simply be put into contact with the paper discs inside their container and the transparent sample holder sealed ready for later on-board analysis.

Samples were also taken for post-mission analysis on the ground to assess the effectiveness of these two new methods. Although this data analysis is still in progress, the new methods have already proved very promising in that they enabled the EuroMir 95 crew to make quick and reliable assessments of the prevailing level of biocontamination aboard the station. In fact, the preliminary assessments indicate that the number of fungine colonies on board is generally larger than expected, whilst there are fewer bacteria colony forming units than was theoretically foreseen.

The experiment equipment was engineered by Alenia Spazio (Turin, I) in collaboration with the University of Perugia (I), under contract to the Italian Space Agency (ASI).

Anbre

This biomechanical motion investigation was designed to test an innovative system, based on a stretched garment fitted with elastomeric sensors, for logging the movements and postures of the crew members under microgravity conditions.

The science programme for Anbre was initially interrupted by a malfunction in the equipment's data handling unit (DHU) thought to be due to a failed microprocessor. Through the prompt collaboration of ESA's European Astronauts Centre (EAC) and ESTEC, a joint ground/space troubleshooting effort in the first weeks of the mission resulted in nominal operation of Anbre by connecting the ESA astronaut's laptop computer to bypass the failed portion of the Anbre electronics.

A first scientific assessement of the Anbre results is currently being conducted using the experiment's memory cards brought back by the Space Shuttle (STS-76 mission) in April 1996, together with the DHU. The latter is currently undergoing a detailed inspection to establish the cause of the malfunction, which may have been due to radiation-related upset events.

Figure 1. View of the Mir space station from the docked Space Shuttle 'Atlantis'

Figure 2. The basic Mir module, now containing hundreds of equipment items associated with past and present experiments

The experimental equipment was developed by Verhaert Design & Development (Kruibeke, B) with scientific supervision from the Laboratoire d'Anthropologie Appliquee (Paris, F), under ESA/ESTEC contract and management.

Elite-S

This human-posture experiment, like the Anbre system, was conceived to examine the effects of microgravity on human posture, both static and dynamic. Data on motorial strategies of movement and perceptual motor relationships were also to be collected, not only in relation to human 'macro-kinematics', but also respiratory functions.

Figure 3. The T2 luminometer, after its final pre-launch inspection at the Baikonur launch site

Elite-S was engineered, under ASI contract, by Alenia Spazio of Turin. It adapted and space-qualified a commercial product (Elite) which the Italian Centro di Bioingegneria in Milan is marketing worldwide for analysing and treating post-trauma motorial disorders, and for enhancing the dynamic performance patterns of various types of athletes.

Unlike the Anbre equipment, the Elite concept does not rely on a suit worn by the crew, but is based on the use of infrared TV cameras. These use special software to discriminate, acquire and store in real time the positions of the crew's limbs during particular movement protocols. The system records the exact positions of the various parts of the body by discretizing them into 'points' identified by detachable 'skin-markers' placed at precise locations on the crew member's body.

Despite the considerable amount of time required to set-up and calibrate the equipment and to perform the measurements themselves, the crew eventually managed to carry out almost all the planned kinematic protocols for the experiment. The large volume of high-quality data collected is now being analysed to build up a three-dimensional database on human posture in space and to update the human-factors analysis tools currently proposed for long-term crewed space programmes.

Biokin

Developed to validate the concept of microbial decontamination of confined atmospheres in space and verify the kinetics of such biodegradation, the Biokin equipment tested the behaviour of one particular type of bacterium, the Xanthobacter autotrophicus, within a simplified biofilter.

The early results have confirmed the suitability of the membrane separator design between the bacteria compartment and the air phase to be treated, and the possibility of inoculating the reactor in space with freeze-dried bacterial cells even after several months of storage.

The first series of such tests on board Mir in late 1995 provided valuable insight into how to improve the inoculation procedure, which was originally based on contemporary breaking of the inoculation capillaries and the substrate capillaries that contained the freeze-dried cells and the contaminant. During the mission-extension phase in 1996, the experience acquired in 1995 was capitalised upon by sending up a second flight model and having the astronaut break the capillaries sequentially, thereby greatly enhancing experiment performance and success.

Parallel experiments based on the same bacterial species catabolizing the same contaminant are now being completed back on Earth for calibration purposes, and to evaluate the kinetics of biodegradation in space versus those of the gravity-bound process on Earth.

The proven ability of selected bacterial micro-organisms to detoxify particular contaminants under microgravity conditions is an encouragement to consider extending such tests to more complex mixtures of air contaminants, aiming at the full-scale implementation of such a system within the International Space Station programme.

In fact, the Biokin air-filtering concept looks very promising not only for space environmental-control and life-support systems, but also for a new generation of ground-based air filtration systems.

The Biokin equipment was designed under ESA/ESTEC contract by the Dutch companies Stork Comprimo (Amsterdam) and Bioclear (Groningen), with support from NIVR, and built by CCM (Eindhoven)

SGS

The microgravity environment and the physical and logistical constraints of a long-term stay in the Space Station call for gas sensors that are both smaller and lighter than the bulky and costly gas-chromatograph/mass-spectrometer type equipment normally used for high-precision gas monitoring on the ground.

The purpose of the experimental Smart Gas Sensor (SGS), developed by RST (Warnemünde, D) under ESA/ESTEC contract and supervision, was to engineer and test two different types of gas-sensor arrays: one composed of organic polymers, the other based on an array of micro-balance oscillators.

Having installed the SGS box and the laptop computer in the module or space to be sampled, the crew had to activate the SGS's pump to draw ambient air to the SGS's inlet. The signals provided by the multi-element sensors were processed in real time and outputted to the portable computer for display in graphical form to the crew.

The equipment was operated extensively throughout the mission, including times when particular events might have caused the release of interesting gases, such as during the EVA phases and during the repair of a leak in one of Mir's thermal-control-system circuits.

Approximately 60 Mbytes of data were collected, covering about 40 of the mission's 180 days. Some software-related problems were reported with the laptop, again probably due to the ionising radiation environment aboard Mir.

Although final data evaluation is still in progress, the SGS was certainly proved capable of providing a complete 'smell-pattern' for the Station. It confirmed the ability of Mir's environmental control system to purify the onboard air very effectively during the crew's rest periods. Events like public-relations link-ups, with all crew members gathered in the main Mir module, returns from EVAs, station cleaning and food preparation were all detected and flagged in a timely manner by the SGS sensors.

With a view to the SGS's potential application on the International Space Station, further tuning work has to be carried out on its sensors to avoid confusion between very similar substances (e.g. butanol for ethanol, as occurred during the EuroMir 95 mission) and to equip the unit with simple visual/audio features to alert the crew quickly to any out-of-tolerance readings.

Figure 4. The RJC experiment box, belted into place aboard Mir

RJC

The Robotics Joint Controller was developed and integrated, as part of the Italian 'Spider' programme, by Tecnospazio (Milan, I) under ASI contract. Its nominal objective was to assess the disturbances to the microgravity environment induced by various velocity and acceleration profiles of a robotic joint. The EuroMir extension programme in 1996 allowed the science team to gather additional data on the possible influence of single-event effects, disturbances in transient phases, and possible performance degradation due to long-term operation (one week).

The on-going analysis is quite complex and definitive results are not yet available, but

LESSONS LEARNT FROM EUROMIR 95

Many useful lessons were learnt both during the preparations for the EuroMir 95 mission and during the flight operations themselves, lessons that can be put to good use for ESA's participation in the International Space Station programme.

Experiments

Lesson learnt: Scientific procedures and operational protocols should be similar if not identical for analogous experiments.

Such synergy reduces the time needed for development, training and onboard operations, as well as increasing the scientific return due to better data correlation. This approach should have been implemented for the Anbre and Elite-S experiments, which were conceived, developed and operated totally independently despite the obvious analogies.

Lesson learnt: Avoid interfaces between experiments that have never been flown before.

During EuroMir mission preparation, downlinking of the Maglev and Elite-S video information by using VISC was considered. This option was eventually dropped but if it had been implemented, the Maglev and Elite-S experiments would have been negatively impacted by the problems that beset VISC (reported above).

Lesson learnt: There should be one technical coordination interface only between the ESA project and the payload funding authority, which should attend all project reviews and major work events.

During mission preparation, the T2, Elite-S and RJC funding authorities requested that all technical, scientific and operational information be sent in parallel to both themselves and the actual payload developers and engineering experts in industry. This resulted in considerable confusion. Further inefficencies occurred at the various development, integration, qualification and acceptance milestones (e.g. flight-model pre-acceptance tests) due to the limited availability of the funding-authority representative. A unique and continuous interface is mandatory for programmes of this nature.

Lesson learnt: Experiment operations should be fully rehearsed on the ground during the development phase.

For instance, the complex installation, calibration and science protocol procedures for the Elite-S experiment were not tried out in a realistic fashion until just one and a half months before launch. This resulted in major changes to the operational documentation at a very late stage and also caused unease during the acceptance testing with RSC Energia. It also resulted in substantial crew-time overruns during the mission itself.

Lesson learnt: Flight-model spares (FM2) should always be produced as recurrent units for long-term missions. When no FM2 is available, a technology model (TM) should be FM-representative although non-space-qualified. Either the FM2 or the TM should remain at the payload-developer's site.

Flight-model spares were launched during EuroMir 95 to support unplanned science sessions, as in the case of Biokin, or could have been launched if available to replace partially failed flight models (e.g. VISC and Anbre). In addition, FM2s or high-fidelity TMs are necessary to support real-time upgrading of mission objectives or for high-fidelity ground troubleshooting with the equipment experts (e.g. crash activities required for Anbre, SGS and RJC).

Lesson learnt: Experimental equipment mockups for configuration/accommodation studies can be passive models representing dimensions and crew interfaces only.

The full-scale mass mockups originally requested by RSC-Energia for the mission integration phase did not prove to be really necessary in practice; full-scale dimensional mockups only, as were eventually delivered for the technology experiments, would have been more than adequate.

TECHNOLOGY EXPERIMENTS

Lesson learnt: Formal readiness reviews should always be held at ESA level prior to conducting acceptance tests with the responsible in-orbit system operator (i.e. RSC for EuroMir 95).

During the Technology Experiments' development and acceptance phases, certain hardware and documentation was submitted to official acceptance testing with the Russian authorities before being complete or functionally ready, causing major time and efficiency losses for all concerned and resulting in time-consuming and ineffective reviews (e.g. T2 and Elite-S, Maglev and VISC).

Lesson learnt: Employ design solutions, processes and materials previously qualified and flown wherever possible in new payload development.

During the EuroMir 95 programme, some electromagnetic-compatibility testing could be skipped thanks to close design similarities with already space-proven equipment. Similarly, certain materials could be 'qualified' on the basis of their similarity to analogous/identical alloys, elastomers or composite materials that have already been flight-qualified.

Lesson learnt: A contractually agreed payload-accommodation handbook is necessary to control payload-to-system interface requirements and simplify payload design, development and integration.

For instance, major reworking of payload documentation and hardware proved necessary in some cases due to unclear and frequently changing requirements from the Mir authorities (e.g. electrical current density requirements affecting payload electrical subsystems and wiring). This problem is de facto already solved for the International Space Station, given the very complete requirements/specifications bibliography which is kept under strict configuration control.

Human factors analysis

Lesson learnt: Do not invest heavily in such interior-design areas as the selection of space-laboratory colour schemes or the development of new crew restraint systems.

The long-term Russian experience with habitability issues, confirmed by the EuroMir flight crews, shows that much of the money being spent on human-factors analysis and prototyping is actually wasted effort because most of a module's interior is quickly covered with hardware and hanging harnesses.

In addition, unlike some current Space Station/Columbus human-factors engineering concepts, the existing Mir crew restraints do not directly transmit crew-induced vibrations to microgravity payloads.

Crew training

Lesson learnt: High-fidelity system training should be carried out with the system-engineering model.

In the last twelve years the Russian long-term spaceflight programme has been implementing such a concept by using the Mir Space Station engineering model for both high-fidelity engineering and crew training. With appropriate facility loading and configuration control, such training can be conducted with no impact on engineering activities, thereby avoiding duplication of hardware, computer systems, manpower and infrastructures.

Lesson learnt: Integrated payload-to-system training is needed only for major experimental facilities with complex system interfaces. Such training, when deemed necessary, should be performed with the system-engineering model.

In line with the approach described in the previous paragraph, RSC-Energia and Star City have applied this concept in training crews since the early 1980s. In fact, eight of the nine EuroMir 95 experiments were trained upon in a stand-alone manner with the help of simple ground-support equipment qualitatively speaking the experimental equipment performed as expected and gathered the requisite data. A thorough scientific evaluation of these data and possible recommendations for robotic-joint technology for future space applications, including the automation of microgravity laboratories for the Space Station, will be available later this year.

REM

The purpose of the externally mounted Radiation Environment Monitoring experiment, developed at ESTEC, is to monitor the radiation environment in Mir's high-inclination orbit to improve currently available models of the charged particles that surround the Earth, many of which are based on data from more than twenty years ago and not compatible with contemporary geomagnetic field models and do not reflect well the known solar-cycle dependence.

The REM equipment was first delivered to Mir in 1994 and is still active. Its simple design is based on two independent silicon detectors with different types of shielding. The energetic particles impacting the detectors are counted and the relevant data are acquired and stored.

Regretfully, during the mission poor data return has proved a problem in terms of both quantity (a few days per month instead of daily) and quality (the data that were received contain quite some errors). Work is proceeding together with our Russian counterparts to recover the 'missing' raw data and orbital parameters in order to be able to complete a comprehensive scientific evaluation.

T10 VISC

In recent years, ESA has conducted many experimental telescience sessions in cooperation with leading European science and technology teams. The concept of having a remotely controlled video switcher and mixer to handle real-time visual information from Space Station experiments (e.g. video, audio and alphanumeric data) led to the design and development of this Video Integrated Services Controller (VISC), which was built and assembled by NTE (Barcelona, E) under ESA/ESTEC contract.

Late delivery of the final revision of the VISC video board by its US supplier did not allow digital video input mixing functions to be incorporated into the VISC flight unit for Mir. However, numerous tests involving the Station,

Figure 5. The EuroMir 95 crew enjoying a well-earned break in their hectic six-month work schedule

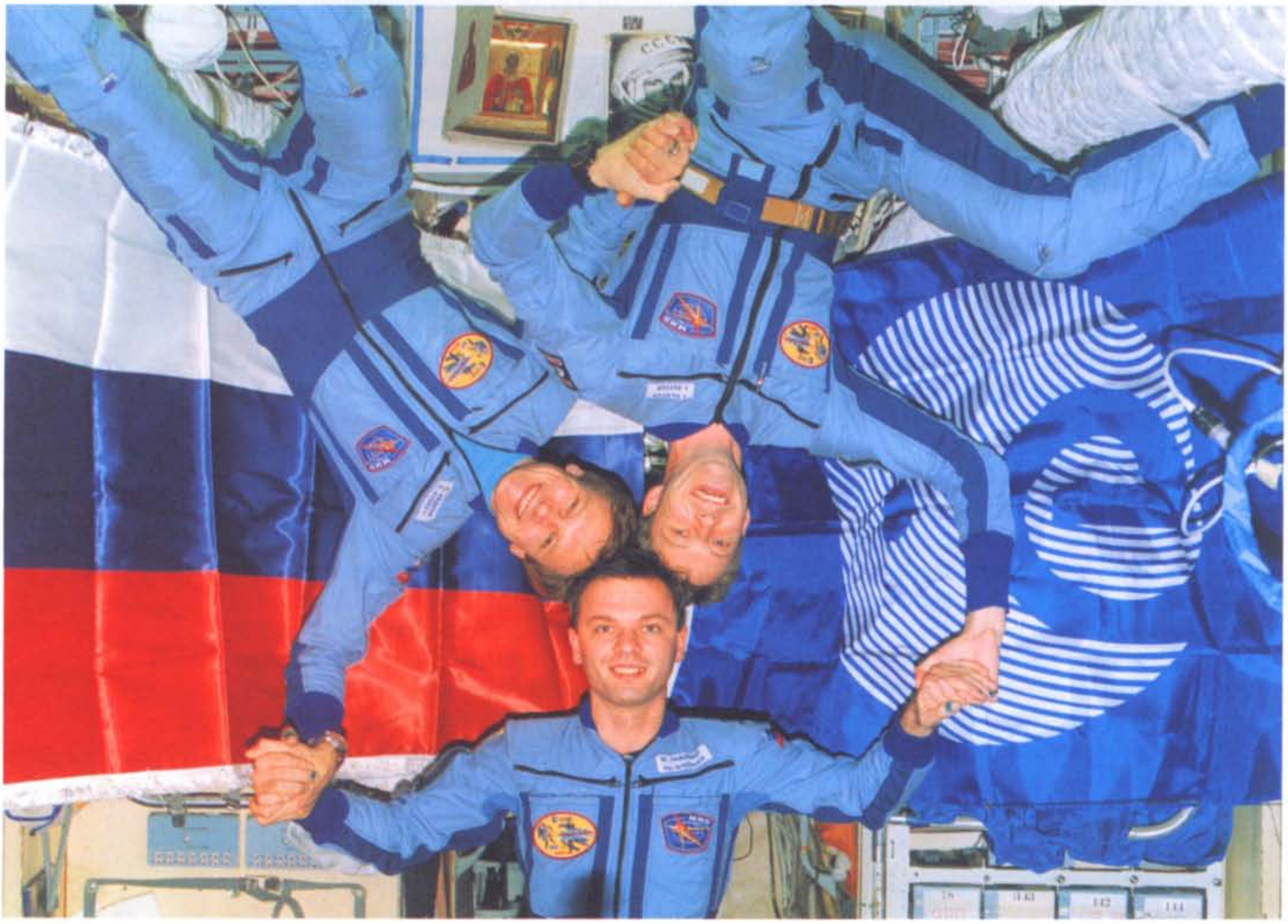

Figure 6. The Russian and ESA EuroMir 95 team, gathered at ESTEC in Noordwijk in September 1994 for an experiment flight-model acceptance review

its Russian ground centres and the ESTEC user centre have shown that the available features of the VISC multimedia communication system function well. For instance, Mir-to-ground exchanges of graphical annotations on VISC screens were successfully demonstrated, as well as ground control of onboard TV-camera outputs for downlinking.

Despite some initial shortcomings, VISC proved itself capable of enhancing telescience space operations and crew-ground interactions for the Space Station era.

Maglev

The Magnetic Levitation Experiment equipment was developed by ESA/ESTEC to demonstrate a simple and inexpensive technology for passive magnetic fluid levitation in microgravity, having as a scientific by-product interesting data on thermally-induced Marangoni convection generated within the levitation cell.

The equipment is small enough to be held in one hand. Its key lies in the generation of a levitating central force field by means of an array of permanent magnets acting on the test cell, which contains a transparent ferro-fluid and a non-magnetic levitation sample (an air bubble was the target object to be levitated).

During the mission, the Mir crew and the ground team (via the video downlink) were able to analyse visually the good stability of the above trapping mechanism, even when the bubble was 'disturbed' by Marangoni convection flows generated at the ferrofluid/air interface by induced temperature gradients.

The concept's viability having been proved during the 1995 experiment sessions, the EuroMir programme extension in 1996 allowed further checks to be made on the levitation system's stability in the presence of transient forces applied externally to the test cell.

All in all, this experiment was a great success, especially given its extremely low development and integration costs.

Conclusions

The extremely positive outcome of the EuroMir 95 programme has to be seen not only in the light of its scientific and technological achievements, but also in the fact that as a Space Station precursor programme it has given ESA clear guidelines as to how to proceed in order to drastically enhance the design and utilisation of its contribution to the International Space Station.

Not least, various results from the above experiments that formed part of the EuroMir programme will provide added value to quite a number of new Earth-bound technologies being developed to support, and ameliorate the problems of, everyday life on our planet.

Acknowledgement

I would like to thank the colleagues who provided inputs to this article, in particular R. Binot and H. Wessels from ESTEC, and V. Cotronei from ASI.

Towards Reusable Launchers – A Widening Perspective

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One of the prime tasks of the Agency, identified in the Report of ESA's Long-Term Space Policy Committee (LSPC) endorsed by the Ministers at their Toulouse Meeting in October last year, is to search for ways to reduce the cost of access to space and thereby open up new markets. One possible approach is that of launcher reuse. Because all such concepts envisaged so far require advances in technology before possibly becoming of potential economic interest, the Agency has begun a programme called FESTIP (Future European Space Transportation Investigations Programme), in which reusable launcher concepts are being studied and the corresponding technology work is being done.

This article presents some possible reusable launcher design options in the context of a scenario that might lead to a technological convergence between space vehicles and high-speed global aviation.

The ideal reusable launcher

The ideal reusable launcher would be analogous to a normal aircraft in that it would be able to take off from many possible bases on Earth, enter the desired orbital plane, accelerate to orbital velocity, release its payload, de-orbit, dissipate its kinetic energy and land at the take-off base to be readied for its next flight after a quick turn-around. The vehicle would maintain physical integrity during a mission, would be flown 'very often', and its cost per flight would be compatible with the value of the missions undertaken. The vehicle would also be able to abort its mission any time in the case of mishap and land intact with its payload. This ideal vehicle is the 'single-stage-to-orbit reusable rocket launcher', or SSTO-RRL.

The value of the 'single stage' concept is that the vehicle maintains its integrity throughout its lifetime. This integrity, which results in the minimisation of the inherent interfaces, is a major factor in the vehicle's dependability. Indeed, the majority of today's practical transport systems are also 'single-stage' vehicles, which include aircraft, ships, cars, etc.

So far, however, all space launchers are staged to orbit and expendable (with the exception of the US Space Shuttle System) and there is no SSTO-RRL as yet, despite its apparent desirability. Clearly, something must be standing in the way of achieving this 'ideal' vehicle.

The problems posed by SSTO-RRLs

Because rocket propulsion is mandatory to accelerate to orbital speed in vacuum, the most logical design option is to use rocket propulsion from take-off until orbit insertion. Both gravity and drag losses must be overcome on the trajectory to orbit. The ideal velocity increment, ΔV, required from an SSTO-RRL is then about 9000 m/s in order to reach a Low Earth Orbit (LEO). All further considerations concentrate on reaching LEO, because this is the most difficult part of gaining access to space and the major hurdle to be mastered in terms of reusability.

The mass that can be accelerated into orbit using rocket propulsion is given by the equation:

$$M_1 / M_0 = \exp(-\Delta V / V_E)$$

where M_0 is the mass at take-off, M_1 is the mass which has received the ideal velocity increment ΔV, and V_E is the ejection velocity of the rocket engine.

For a given ΔV, which is mission-imposed, the mass ratio M_1 / M_0 increases with increasing V_E. The highest practical rocket ejection velocities are achieved by burning hydrogen with oxygen in a combustion chamber and ejecting the produced gases through a convergent/divergent nozzle. When averaged over the trajectory, the exhaust velocity V_E is in the order of 4000 m/s. The corresponding mass ratio to reach LEO is:

$$\begin{aligned} M_1 / M_0 &= \exp(-\Delta V / V_E) \\ &= \exp(-9000/4000) = 0.1054 \\ &= 10.54\% \end{aligned}$$

This means that $100 - 10.54 = 89.46\%$ of the take-off mass must be made up of propellants, and that just 10.54% of the trade-off mass remains available for the tankage to contain the propellants, the engines, the structures, the equipment, and last but not least the payload. Assuming that the payload is 1% of the take-off mass, the mass fraction left available to build the complete launcher is 10.54 − 1 = 9.54%. This is not very much, and we have already assumed the highest performing propulsion system possible (cryogenic propulsion).

Mass ratios of the order of 10% are achieved today with expendable rocket stages, but are a nearly impossible requirement for a reusable vehicle, which is more stressed during its lifetime and which must carry the additional provisions for recovery and reuse. Because today's rocket propulsion is already quite near to its theoretical maximum, the whole burden of achieving such small mass ratios falls on the materials from which the launcher is built. Such launchers are, however, still studied within the FESTIP initiative (Fig. 1) in order to define the areas in which technology advances would be most effective.

Means for increasing the mass ratio

If the mass ratio allocated to the SSTO-RRL could be larger, the vehicle might become more feasible or more robust to use. The options offered by the rocket equation for increasing the mass ratio are to increase V_E, or to decrease ΔV, or a combination of the two.

If V_E were increased by 10% from 4000 m/s to 4400 m/s, the mass ratio would become

$$M_{11} / M_{10} = \exp(-9000 / 4400) = 0.1293$$

Again assuming 1% for the payload, the mass available for the vehicle becomes

$$12.93\% - 1\% = 11.93\%$$

which represents a percentage increase of

$$(11.93 - 9.54) / 9.54 = 25.1\%$$

with respect to the nominal SSTO-RRL, which is quite a significant gain.

Increasing V_E is equivalent to finding a propulsion system which produces the required thrust while consuming less propellant. For example, the apparent V_E of propellants carried aboard a rocket increases when some of the products ejected are taken from the ambient air instead of having to be carried onboard from the start. In general, however, increasing the V_E of a rocket motor with the help of the atmosphere is a complex problem to which Europe cannot expect an early solution. A typical configuration of this type, shown in Figure 2, is the SKYLON (UK), derived from HOTOL.

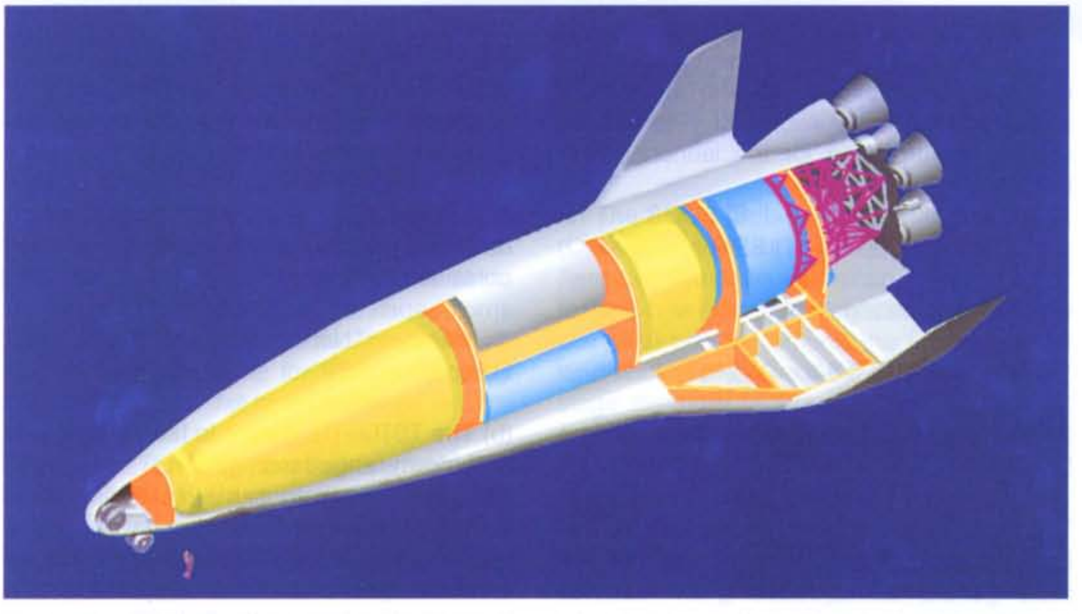

Figure 1. A possible single-stage-to-orbit launcher studied within ESA's FESTIP initiative

Turning now to the effect of a reduction in velocity increment, if the required ΔV were reduced by 10% from 9000 to 8100 m/s, the mass ratio would become

$$M_1 / M_0 = \exp(-8100 / 4000) = 0.1320$$

If we still want a 1% payload in orbit, the payload MP_0, ejected at 9000 − 8100 = 900 m/s short of orbital velocity, must carry an additional propulsion system. Assuming a storable bipropellant system having an effective exhaust velocity of V_{E2} = 3000 m/s, the mass fraction for the payload is

$$MP_1 / MP_0 = \exp(-900 / 3000) = 0.7408$$

The mass ejected 900 m/s short of orbital velocity must therefore be 1 / 0.7408 = 1.350%

Figure 2. A possible single-stage-to-orbit launcher with combined air-breathing and rocket propulsion

of the launcher take-off mass to again have a final payload mass in orbit of 1%. The net mass ratio remaining for the launcher itself becomes

$$13.20\% - 1.350\% = 11.85\%$$

which represents a gain of

$$(11.85 - 9.54) / 9.54 = 24.2\%$$

with respect to that required for the pure SSTO-RRL.

Therefore, reducing ΔV is as effective in creating a mass margin as is increasing V_E. In more general terms, reducing ΔV leads to having more than one stage to reach orbit. As each stage has to deliver only a fraction of the total ΔV, its mass fraction can increase and a more robust design becomes possible.

Staging options for RRLs

(a) The SSTO-AL(air-launched)-RRL

Principle: A carrier aircraft takes the SSTO-RRL to a certain altitude and speed, thereby reducing the remaining DV required to reach orbit. The Interim HOTOL carried on-top of an Antonov-225 aircraft is one such example (Fig. 3).

Drawbacks: The carrier aircraft has a limited payload capability, which constrains the SSTO-RRL's mass at separation. As a result, an air-launched SSTO-RRL becomes as difficult to build as a ground-launched version for which no take-off mass limitations apply. This comment is applicable to any upper stage of any Two Stage To Orbit (TSTO) system, because large vehicles are more effective and have a lower overall mass-ratio capability. Air-launching also involves a dangerous separation in the presence of aerodynamic flows.

Advantages: Air-launching gives launch azimuth flexibility and provides a self-contained flying launch base.

Conclusion: Not a promising solution for Europe.

(b) The TSTO-RTL (return to launch site) and DRL(down-range-landing)-RRL

Principle: Here, a reusable rocket first stage carries a reusable (or expendable) rocket second stage. In the RTL mode, the first stage returns to the launch site after separation. RTL is practical as long as the first stage does not re-enter too far down range, which corresponds to up to 1/4 of the total ΔV required to reach LEO. The FLS as studied by Aerospatiale for ESA in the early 1980s (Fig. 4), the RRL studied in the early 1990s (Fig. 5) and the FSS 9 as studied within FESTIP (Fig. 6) are vehicle's of this type.

Figure 3. The Interim HOTOL launched from the Antonov 225 aircraft

Figure 4. The semi-reusable future launching system studied by Aerospatiale in the early 1980s

Figure 5. A semi-reusable rocket launcher as studied by Aerospatiale in the 1990s

In the DRL mode, the first stage provides a larger share of the total ΔV and is allowed to land down-range of the launch site after separation and re-entry. The first stage returns to the launch site at a later time. The TARANIS, studied by Aerospatiale for ESA in the early 1990s (Fig. 7) was this type of vehicle.

Drawbacks: There are now three aerodynamic configurations to be controlled – the first stage, the second stage when reusable, and the composite – two vehicles to be developed and qualified, and the amount of operations is increased. Staging is optimised for a given technology level and prevents one from deriving full benefit from any subsequent technology improvements. Because of the mass limitations on the second stage, its reusability represents a penalty rather than a cost advantage. A more effective solution is that of an expendable second stage, which could be considered an interesting interim solution.

When implemented with today's technology, the TSTO-RTL/DRL-RRL is not much cheaper in use than an expendable launcher, but it can already offer higher reliability and safety. Launch/in-flight abortability remains limited.

Advantages: Feasible in the near term, if needed.

Conclusion: Not an interesting solution for Europe, in that the expendable Ariane-5 is already a modern launcher with significant evolution potential.

(c) The SOSS (Sub-Orbital Single Stage) OA (Once-Around) RRL

Principle: The down-range capability of the first stage is now extended to the point where it can complete one trip around the Earth so as to land back at the launch base (Fig. 8). The first stage therefore provides almost the total ΔV needed to reach orbit and the payload, ejected in vacuum but still at sub-orbital speed, achieves orbital velocity with its own propulsion system. This principle is comparable to that of the SSTO-AL-RRL, except that now the ΔV complement provided by the carrier aircraft (a large and expensive item) is provided by the payload itself (a small system) and the large sub-orbital stage itself retains the freedom of unconstrained mass at take-off.

Drawbacks: The payload must provide its propulsion into orbit (from 300 to 3000 m/s) to

Figure 6. A fully reusable two-stage-to-orbit rocket launcher as studied within FESTIP

Figure 7. TAKANIS: a fully reusable rocket launcher with down-range landing of the first stage

compensate for the ΔV deficit of the sub-orbital stage. Not all payloads might welcome this, but this requirement could be taken into account when designing them.

Advantages:

For the payload: For the majority of payloads, LEO is not the ultimate destination and many of them already carry an integrated propulsion stage to acquire higher energy orbits. Adding the need to provide the initial impulse to reach orbit therefore does not represent an excessive penalty.

For the launcher: The launcher is now back at the launch site after one revolution. The ΔV needed to circularise and to de-orbit is saved, there is no launcher in-orbit phase with the associated functions and mass, and a high launcher efficiency is therefore possible.

Conclusion: The author believes that the SOSS-OA-RRL (sub-orbital single-stage once-around reusable rocket launcher) can be a very promising solution, the particular features of which are discussed below.

Operating mode of the SOSS-OA-RRL

Let us start by defining a large reusable stage with a given take-off mass, of say 500 tons. Since we do not yet have the technology to achieve the mass ratio necessary for true SSTO operation, we must design the launcher to provide the largest ΔV it can, and leave it to the payload to provide the complement needed to achieve orbital conditions. Keeping the take-off mass constant allows us to freeze the launcher's external shape, so that the aerodynamic database remains valid once established, and the installed thrust can be fixed. The launcher tankage is designed for the full volume of propellants ultimately required for SSTO, and the payload bay is given the volume needed by the largest possible combination of payload with its upper-stage propulsion.

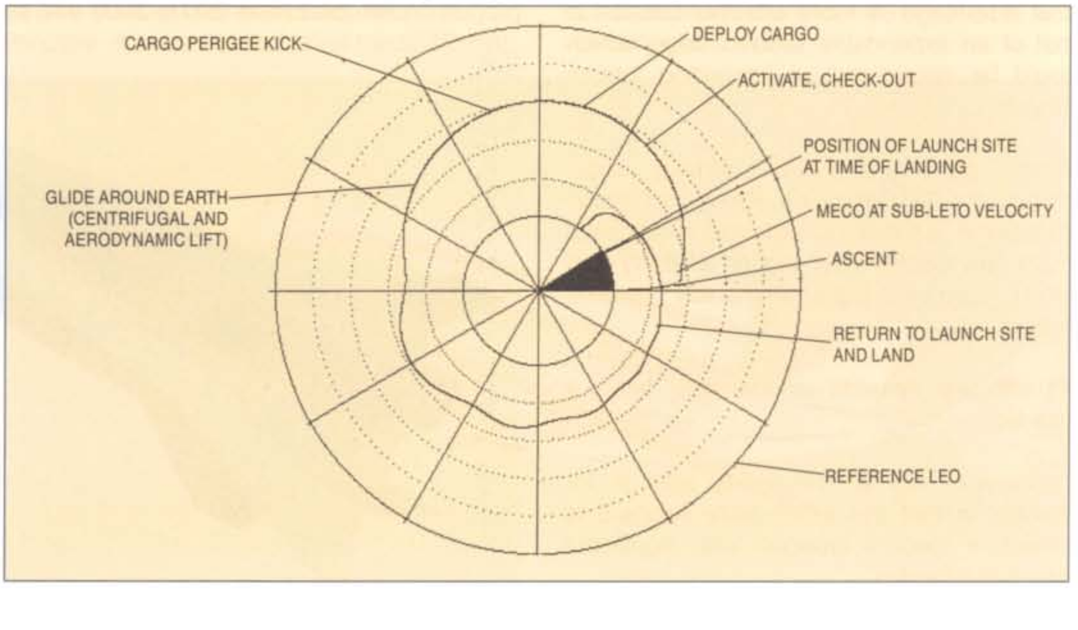

Figure 8. The trajectory of a once-around Earth sub-orbital single-stage reusable launcher

We can now trade-off propellant masses between the launcher and the payload whilst keeping the total take-off mass constant. Depending on the sharing of ΔV between the launcher and the payload, we can achieve a range of payload-in-orbit capability. This approach therefore combines the flexibility and performance robustness of a pure TSTO system with the operational benefits of a single-stage vehicle. We refer to this approach as 'internal staging'.

The SOSS-OA-RRL, when already dimensioned for ultimate SSTO capability, can therefore become an interim single-stage vehicle with which practical experience can be accumulated early in a revenue-generating utilisation environment, whilst still preserving the possibility to upgrade it as technology progresses, without affecting its overall layout. With improving technology, the launcher dry-mass or the propellant mass needed will decrease, the launcher will reach higher speeds, and the propulsion requirements on the payload will decrease accordingly, until a pure SSTO capability becomes possible, should this indeed prove to be an economically viable option.

In a first approximation, the cost of using an SOSS-RRL is constant and independent of the mass of the payload with propulsion it carries, because its take-off mass is constant. The same SOSS-OA-RRL is used for each payload, irrespective of its mass, the only adaptation being the correct loading of propellants and the calculation of the corresponding trajectory. This repeated utilisation should lead to significant cost savings as experience accrues.

Our SOSS-OA-RRL now resembles a truck which has a maximum payload, but can also operate profitably with a partial load.

The value of good high-speed aerodynamics

The velocity deficit of the SOSS-OA-RRL with respect to orbital velocity cannot be too large if we want the reusable launcher stage to complete one turn of the Earth and return to the launch base in a non-propulsive manner. The permissible deficit will depend on the vehicle's aerodynamic qualities during the high-speed re-entry phase: a greater lift-to-drag ratio at hypersonic speed permits a greater passive down-range capability, which permits a larger allowable velocity deficit with respect to orbital speed, which in turn permits a greater launcher dry-mass (at the expense of increased aerothermal problems). Suitable shapes for the hypersonic glide-back flight are lifting bodies (Fig. 9) or waveriders (Fig. 10).

An SOSS-OA-RRL which needs a down-range capability to return to its base therefore makes constructive use of the kinetic energy it received during ascent, instead of simply destroying it as is the case for re-entry from orbital speed.

If the velocity deficit is such that even good aerodynamics do not allow a complete once-around glide, the stage can land after a partial orbit, but then there is the problem of returning it to the launch base, or we can equip it with an auxiliary propulsion system for a powered fly-back to complete the once-around. This powered fly-back could either be ensured by a scramjet for high-altitude, high-speed flight (although there might be thermal problems), or as a subsonic cruise on turbojet power (aerial refuelling with kerosene is a possibility). Again, the better the aerodynamics, the less penalising the cruise-back becomes.

Figure 9. A lifting-body sub-orbital, once-around reusable rocket launcher studied within FESTIP

Vertical versus horizontal take-off

Now that we have a reason to require good aerodynamics for the return flight of the SOSS-OA-RRL, the next step is to use the installed aerodynamics for horizontal take-off (HTO) and lifting ascent on rocket power only. Indeed, the integrated velocity losses with HTO are a little less than with vertical take-off (VTO) on rocket power. A conventional SSTO-RRL must, however, rely on VTO because its required low mass fraction does not permit the implementation of lifting surfaces for ascent.

For a reusable vehicle, however, VTO has unpleasant implications. With VTO, the installed thrust – which translates into number, mass and cost of engines – must lift the vehicle off the pad, must provide the thrust needed to accelerate it, and there must also be a thrust margin for some engine-out capability. The total installed thrust then corresponds to about 1.5 times the take-off weight of the vehicle, only about a third of which does useful work in

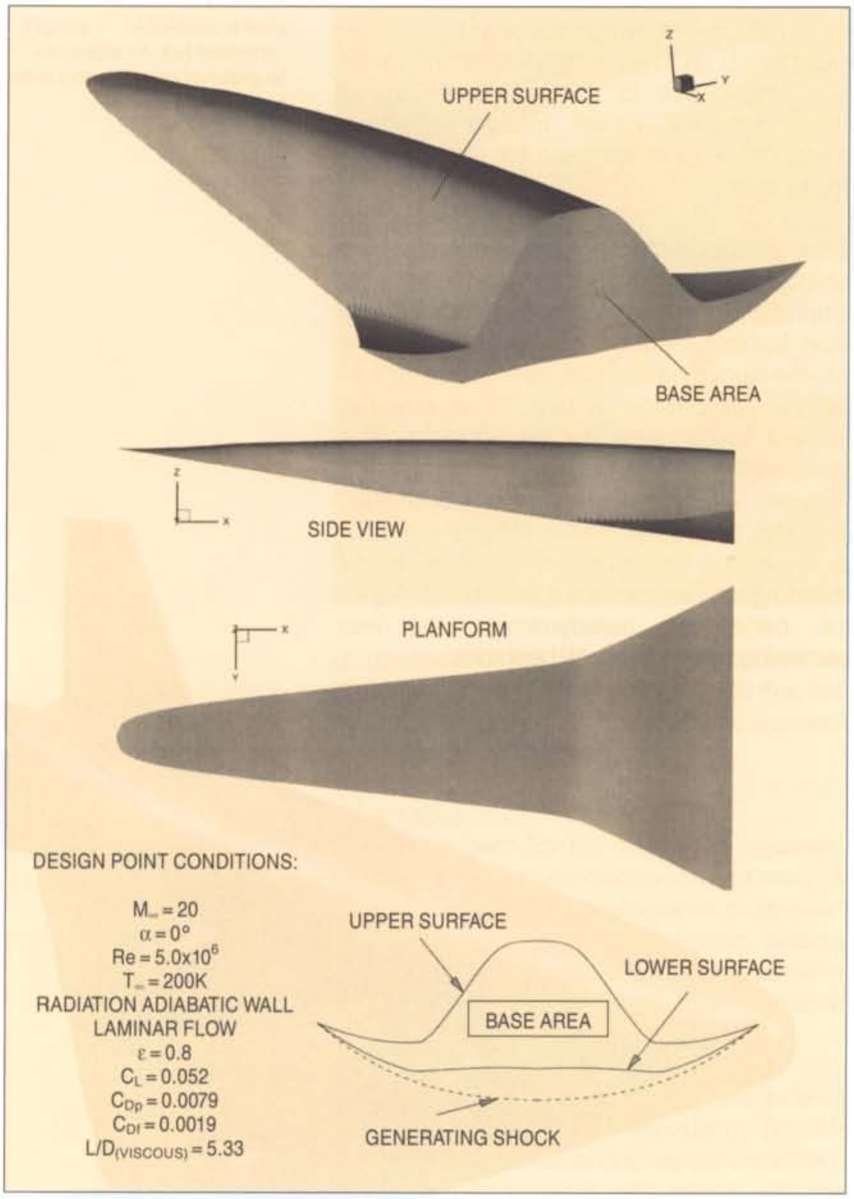

Figure 10. A generic 'wave-rider' shape as studied within FESTIP

accelerating the vehicle during the initial phase of the mission. This installed thrust becomes excessive towards the end of the ascent and engines have either to be throttled back (cost) or shut-off (dead mass into orbit).

Because rocket engines must be located at the base of the vehicle, a high installed thrust shifts the centre of mass of the empty vehicle to the rear and compromises must be made in the aerodynamic shape in order to maintain a controllable vehicle at re-entry.

Even when planning for engine-out situations, VTO remains a dangerous phase and while this is normal for an expendable launcher (if it has to fail, it does not matter where it fails), it is far from ideal for a reusable vehicle. Indeed, until there is enough dynamic pressure to provide aerodynamic control authority, the reusable launcher behaves like an expendable vehicle and the range-safety and vehicle destruct may have to be retained.

Finally, VTO requires a heavy ground infrastructure which is both costly and limits the number of launch bases that one can build.

The SOSS-OA-RRL launcher, which needs aerodynamics for its return flight (and which can afford it because of its higher permissible mass fraction) allows one to exploit the ΔV savings of HTO. However, HTO also has more fundamental advantages. With HTO followed by lifting ascent, the weight of the vehicle is carried by the lift due to the forward speed and only the drag generated by that lift has to be compensated for by rocket thrust. Depending on the aerodynamic shape, the drag generated by the lift is only one half to one quarter of the vehicle's weight. Rocket thrust to accelerate the vehicle at the rate of 0.5 g at take-off is sufficient, so that the total rocket thrust needed by an HTO vehicle is about 0.5 + 1/2 to 1/4 = 1.0 to 0.75 times the weight of the vehicle at take-off. This reduced thrust budget leads to associated reductions in engine mass (which improves the aerodynamic centering) and cost.

HTO also provides an increased engine-out capability and therefore greater safety, at least when implemented as follows. The vehicle can rest on a passive trolley, on a linear ground track a few kilometres long. The vehicle accelerates under its own rocket power until the appropriate velocity is reached, at which point its nose is pushed upwards mechanically causing the vehicle to lift off from the trolley and continue its ascent. Operational advantages of this approach are:

- until the vehicle leaves its trolley, the take-off can be aborted
- once minimum control speed plus a predetermined margin is reached, the take-off can be initiated, but should there then be a loss of thrust the excess velocity is used to stabilise the vehicle and the only thrust needed is that to compensate for the drag, which is about 1/2 to 1/4 of the total installed thrust; the vehicle can dump its oxygen to reduce its weight, thereby increasing the thrust margin, allowing it to turn back and land safely.

With this scenario, rocket-powered HTO could offer the same thrust and safety margins as are now customary for multi-engined aviation.

Finally, the HTO lifting ascent phase prolongs the time spent in the Earth's atmosphere by several minutes, which might allow some form of air-breathing rocket propulsion to be added to the vehicle at a later date, thereby improving the apparent specific impulse of the propulsion system and further increasing the allowable mass ratio.

An eventual boost-glide vehicle for global Earth travel?

By now, our proposed SOSS-OA-RRL has quite striking parallels with conventional aviation: horizontal processing, horizontal take-off, horizontal ascent, gliding or powered hypersonic flight, horizontal landing, and similar engine-out tolerances. The vehicle can cover all speed ranges from low subsonic to nearly orbital, and can evolve through the whole depth of the atmosphere. But such a vehicle might have other applications too, as it is not obliged to make a full revolution of the Earth: it could then serve as a high-speed global transport vehicle.

Indeed, high-speed commercial transport (HSCT) programmes in the USA, Japan and Europe are already devoting significant funds to solving the fundamental technology problems, and the approach being pursued so far envisages cruising at higher speeds (up to Mach 5.5), as a direct extrapolation of today's lower speed aviation. At such speeds, however, global range trip times remain long, the aircraft cruises in contamination-sensitive layers of the upper atmosphere where its engines deposit emissions, the aircraft generates a sonic-boom carpet on the ground, which makes supersonic overflight of land masses unlikely, the aircraft faces severe thermal soaking problems, the propulsion still has to be developed to civilian standards, etc.

The boost-glide approach of the SOSS-OA-RRL is a logical alternative for such global travel: the vehicle is accelerated to high speed (Mach 10?,15?) by rocket (not necessarily O_2/H_2) or by rocket plus air-breathing propulsion, follows a ballistic arc in near-vacuum, re-enters and dissipates its kinetic energy during an equilibrium glide at hypersonic speed and at high altitude. Once this energy has been dissipated, the vehicle can make a conventional landing like a normal subsonic aircraft.

The advantages of boost-glide for global travel are:

- The boost phase is a pure acceleration phase with little energy loss, and takes place over a small area only. Rocket exhausts contain no nitrogen oxides as no air is combusted.
- The ballistic phase is outside the Earth's sensitive atmosphere and therefore has no detrimental effect on the planet.
- The hypersonic glide is at such high altitudes that the sonic boom does not reach the ground and therefore land masses could be overflown at hypersonic speed.
- The vehicle's high speed allows it to benefit from centrifugal force in order to reduce the required lift, which in turn reduces drag and provides a greater operating range for the same initial energy.
- Global travel times are much reduced compared with the supersonic-cruise approach.

Conclusion

Assembling the features described, one can conclude that, *with today's emerging technologies*, launcher reusability offers the opportunity to serve both the space-launch and global-travel markets with one type of vehicle: the sub-orbital single-stage reusable rocket launcher. The vehicles themselves would differ in detail, depending on their exact roles, but they would rely on a common technological base.

Such synergy would be to the benefit of both communities: it would enlarge the technology base available for space activities, it would spread the resulting development costs, it would amortise more rapidly all investments made, and it would stimulate a new approach to travelling around our planet, which in turn could prove a strong motivator for the younger generation to pursue a scientific/technical career.

Space has the potential to become a very large industrial park, stimulated by more routine and less costly access to space in the same way that global markets have been facilitated by the growth and falling cost of today's Earth-bound transport systems. Assessment of the possibilities for making this happen deserves commensurate spending for exploratory work. ESA's FESTIP programme will hopefully contribute to this goal.

The Dynamics and Control Analysis Package (DCAP)

– A versatile tool for satellite control

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In recent years, space-system design has shown a clear trend towards increasingly complex configurations. Typical examples are the use of several flexible components (antennas and solar arrays), the need for deployment and retrieval mechanisms, the demand for high-precision pointing systems, and the increase in mission scenarios implying the assembly of large structures in space. This trend has also caused an evolution towards a multi-disciplinary design approach, particularly in the area of dynamics and control.

This article presents a summary of the development work that has been undertaken during the last ten years by Alenia Spazio under ESA contract, culminating in the production of DCAP – the Dynamics and Control Analysis Package.

Overview

DCAP is a suite of fast, effective computer programs that provides the spacecraft analyst with a powerful tool for designing and verifying the dynamics and control performance of coupled rigid and flexible structural systems. The software modules that it contains can be grouped into four general categories (Fig. 1):
- pre-processing
- processing (time and frequency domains)
- post-processing
- utilities.

Communication between the modules is achieved via the dedicated file structure shown in Figure 2, in which the logical hierarchy of the DCAP programs is also illustrated.

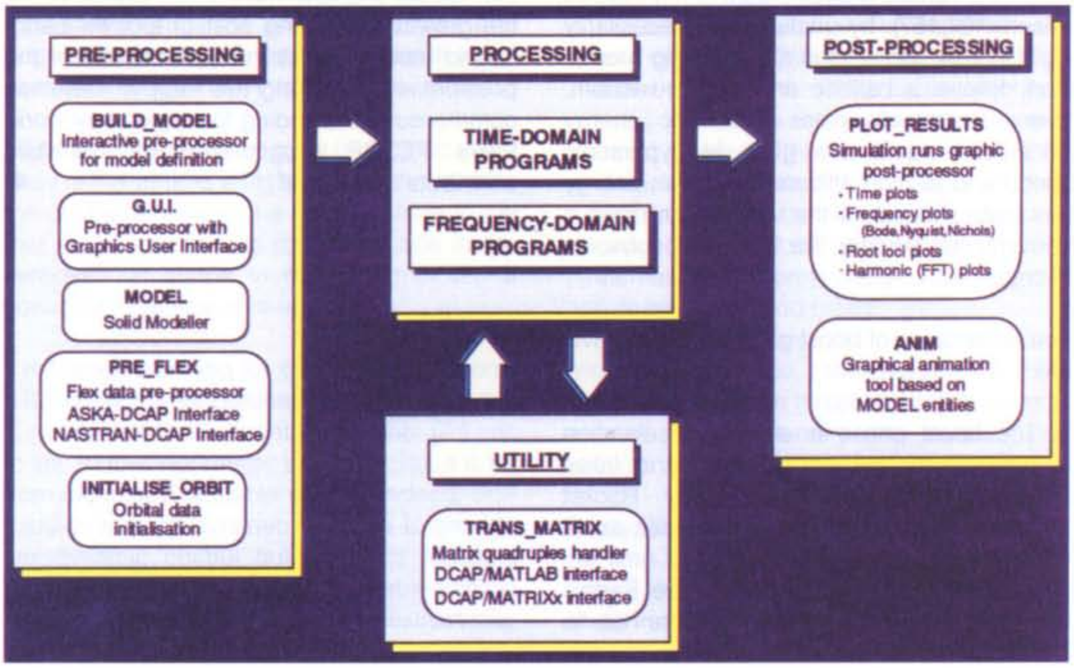


Figure 1. The DCAP software modules

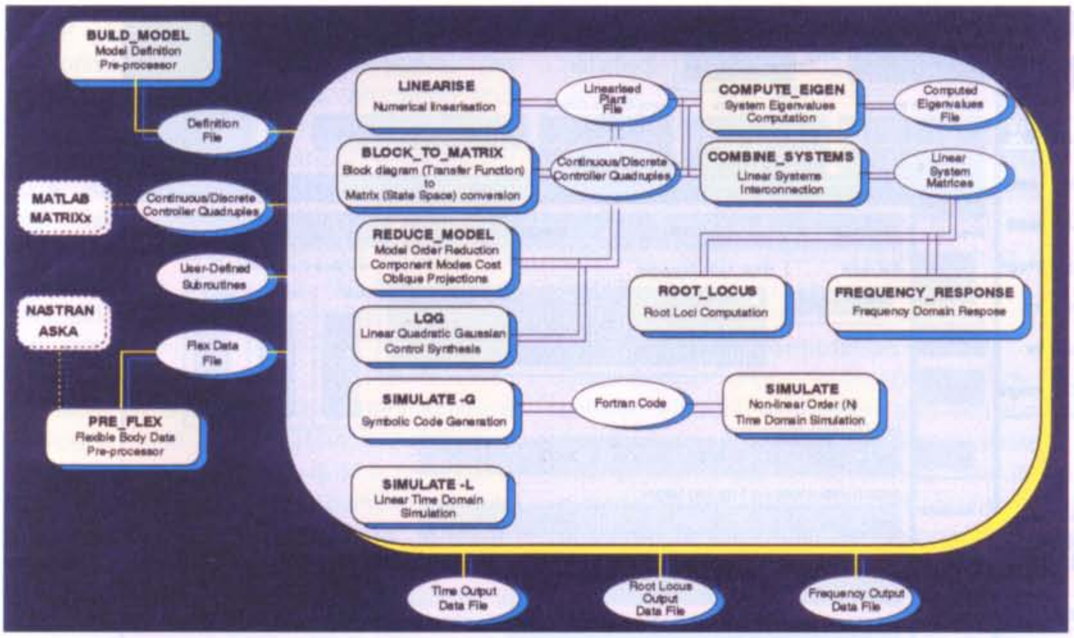


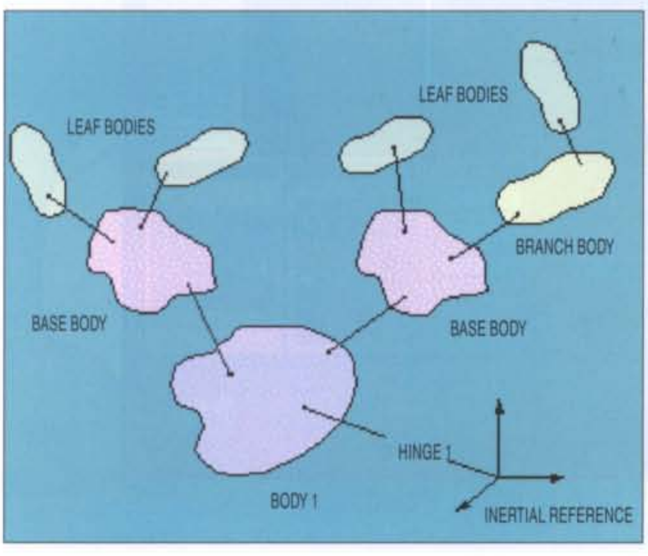
Figure 2. Modules and file interfaces

The package provides the user with an outstanding capability to model, simulate and analyse a complex multi-body system. The latter can be connected in open- and closed-loop topologies (Fig. 3), where relative motion is defined through 'hinges'. Each hinge allows from zero to six relative degrees of freedom, as it can be free, locked or constrained to pre-defined motion.

From a general viewpoint, the DCAP model is the combination of four components:
- 'structure' or 'plant': the multi-body topology itself
- 'sensors': the feature that allows the extraction of system motion information for performance monitoring
- 'actuators': the feature through which forces and torques are applied to the structure
- 'controller': the part of the system driving the multi-body structure in order to achieve the allocated objective.

DCAP Capabilities

- Rigid and Flexible Body Chains
- Open- and Closed-Loop Topology
- Six Degree-of-Freedom Hinges
- Large-Angle Rotations
- Linear and Non-linear Time Domain Simulations
- Order (N) Algorithm
- Symbolic Code Generation
- Orbital Environment
- Built-in Sensors and Actuators
- Non-linear Devices (including Coulomb Dampers)
- Numerical Linearisation
- Continuous/Discrete/User Controllers (Transfer Function, State Space, Block Diagram)
- File Interface to MATLAB and MATRIXx
- File Interface to NASTRAN and ASKA
- Frequency Response
- LQG and Model Order Reduction
- Interactive Pre- and Post-processing.



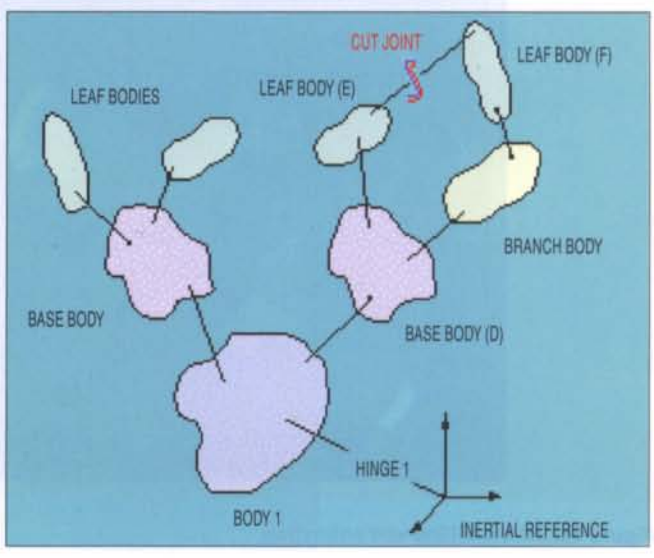


Figure 3a,b. Open-loop and closed-loop tree topologies

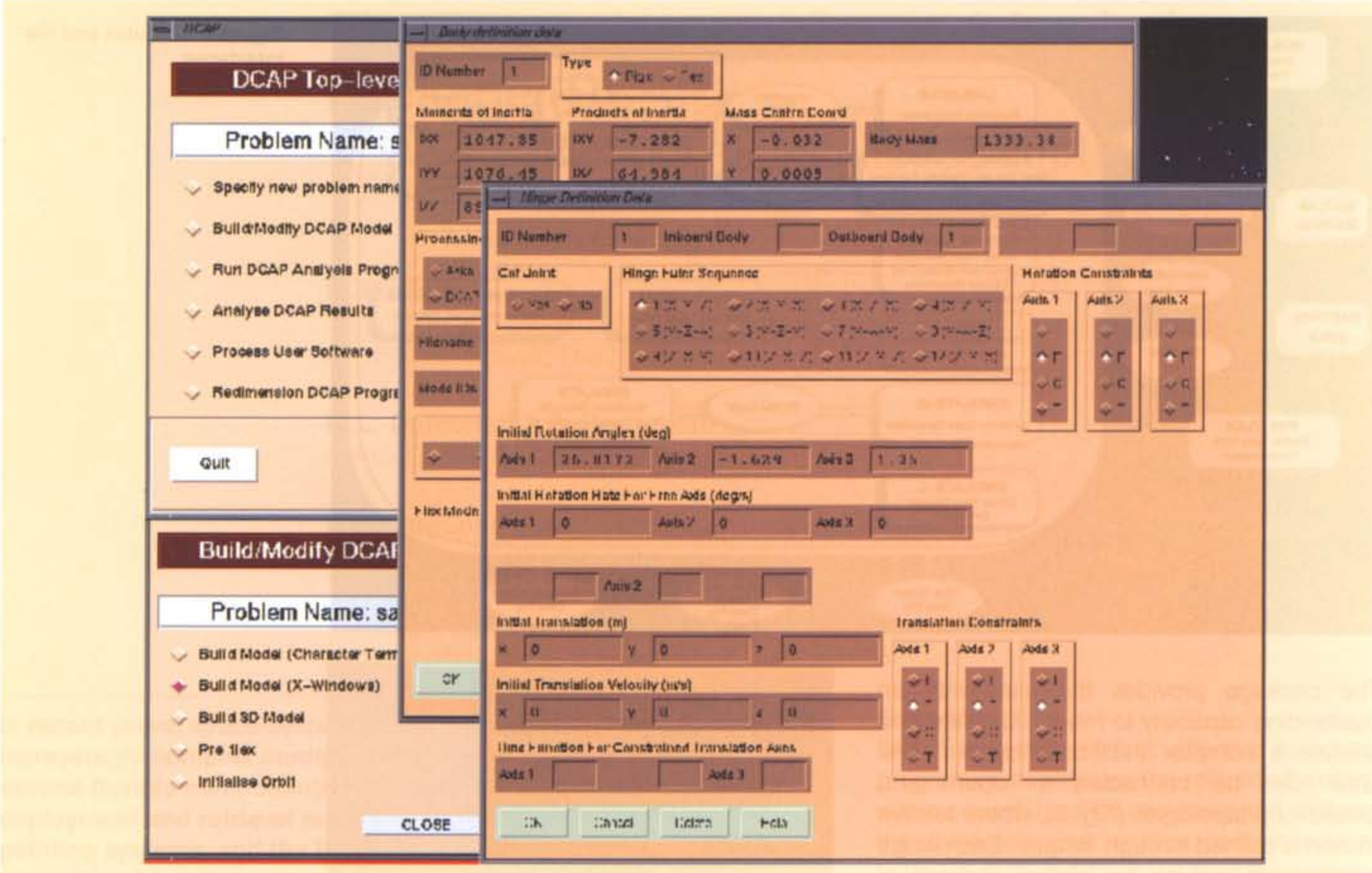


Figure 4a. Menu-driven environment

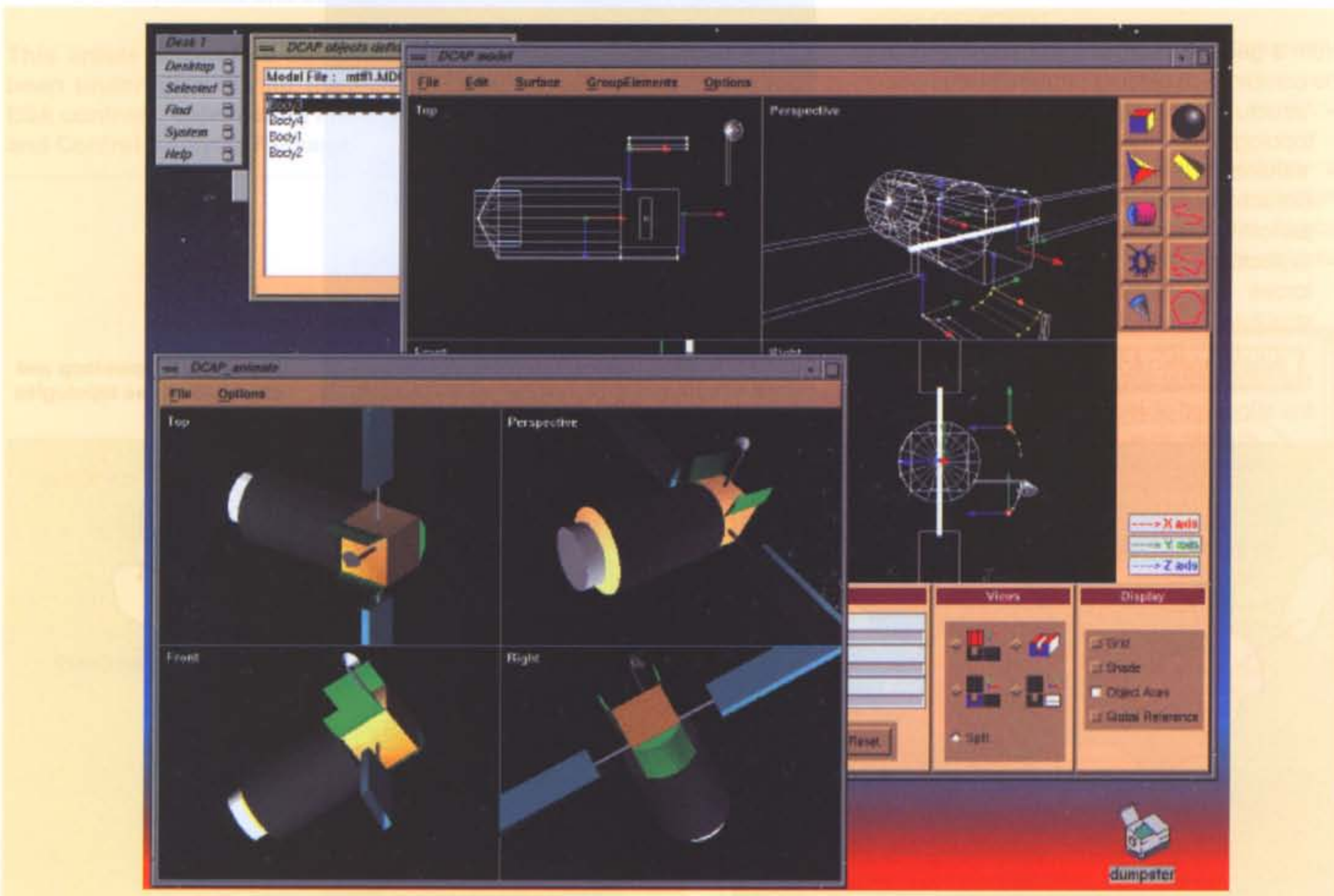


Figure 4b. 3D modelling and animation

DCAP provides an interactive menu-driven environment (Fig. 4a), which assists the user in defining the model, preparing and executing the simulation run, and analysing the results. The model definition is supported by a user-friendly X/MOTIF-based graphical user interface that allows both for the interactive inputting of the data required by each building block (Fig. 4a) and for the geometrical three-dimensional (3D) modelling of the structure (Fig. 4b).

Interfaces to popular finite-element software packages such as NASTRAN (MSC and COSMIC) and ASKA, are available and give a direct capability to define complex flexible structures. Similar interfaces are provided to control design packages like MATLAB and MATRIXx. The modelling capability is completed with the possibility of user-defined software integration, allowing for the use of specific features (sensor and actuator dynamics, user controller, etc.) not directly included in the package's library.

The results analysis is supported by a specific plotting package that can handle time-domain plots, harmonic analysis (direct and inverse FFT), and Bode, Nichols, Nyquist and Root locus charts. Performance can also be inspected via a powerful 3D animation tool, which helps the user to visualise the simulation results (Fig. 4b).

The core of the package consists of the computational modules, particularly oriented towards the simulation of the non-linear dynamics of multi-body systems. In addition, programs for numerical linearisation, matrix representation manipulation (state space) and system combination allow linear problems in both the time and frequency domains to be handled.

The current DCAP is running on VAX/VMS computers and on UNIX (Sun, Silicon Graphics) work stations, and the software package is complemented by a full set of manuals (User, Theory, Demonstration and Installation).

DCAP dynamics formulation

Considerable efforts have been made to achieve efficient formulation and solution of the dynamic equations of multi-body systems. The solution must be developed carefully to provide the requisite fidelity and accuracy, and at the same time minimise the computational costs associated with the time-history simulation. The formulation for the dynamics of multi-rigid/flexible-body systems, as defined in the DCAP software, is based on Kane's method and it exploits a dedicated symbolic manipulation preprocessor. The equations are first derived based on body pairs (Fig. 5), i.e. the basic dynamics solution is formulated for recursive operations: given a body *j*, its motion is completely known from the knowledge of inboard body *(L(j))* motion, relative joint motion, and active forces due to control-system actuators or the environment surrounding the body. In particular, this approach implies three basic steps:

- a first 'forward sweep' from the 'core' body (body 1 in Fig. 3) to the 'leaf' bodies to compute the kinematics
- the implicit computation of the acceleration of each body in terms of the external forces and torques acting on it, and of the acceleration of the body directly inboard; this part of thesolution process is identified as the 'frontal part', and it starts from the

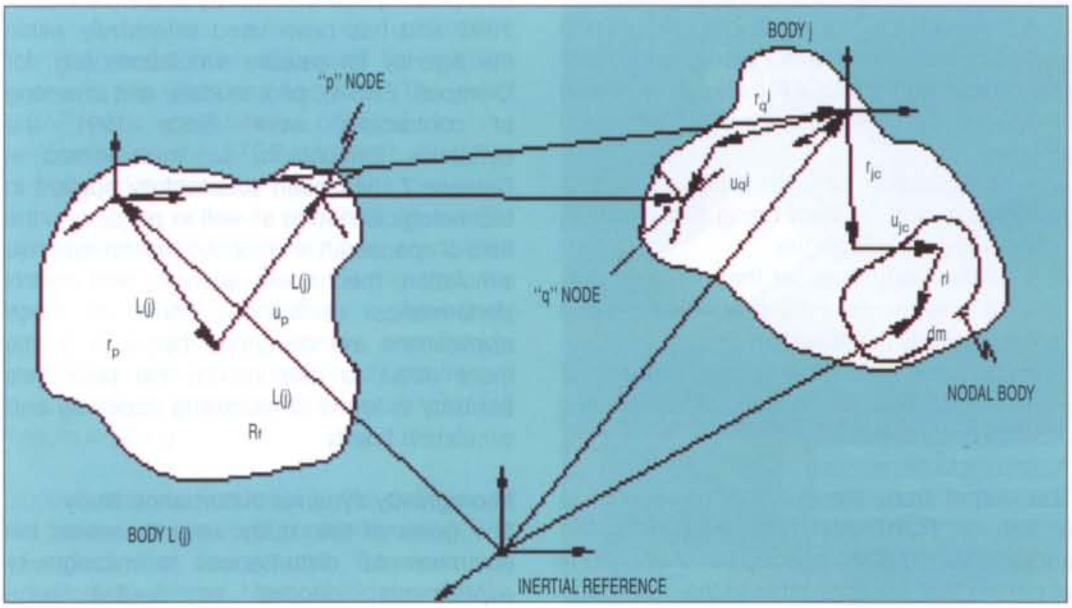


Figure 5. Body *j-L (j)* pair

'leaf bodies' and ends when the 'core' body is reached
- a second 'forward sweep' to explicitly compute the acceleration of each body via a back-substitution process.

This scheme allows one to avoid the explicit computation of a system mass matrix and its inversion, and it results in a minimum-dimension formulation exhibiting close to *Order(n)* behaviour, *n* being the number of system degrees of freedom.

Symbolic processing of the equations of motion can result in a substantially more efficient simulation. This increase in efficiency is achieved through simplifications that are possible because of special configuration characteristics, as well as arithmetic and algebraic simplifications.

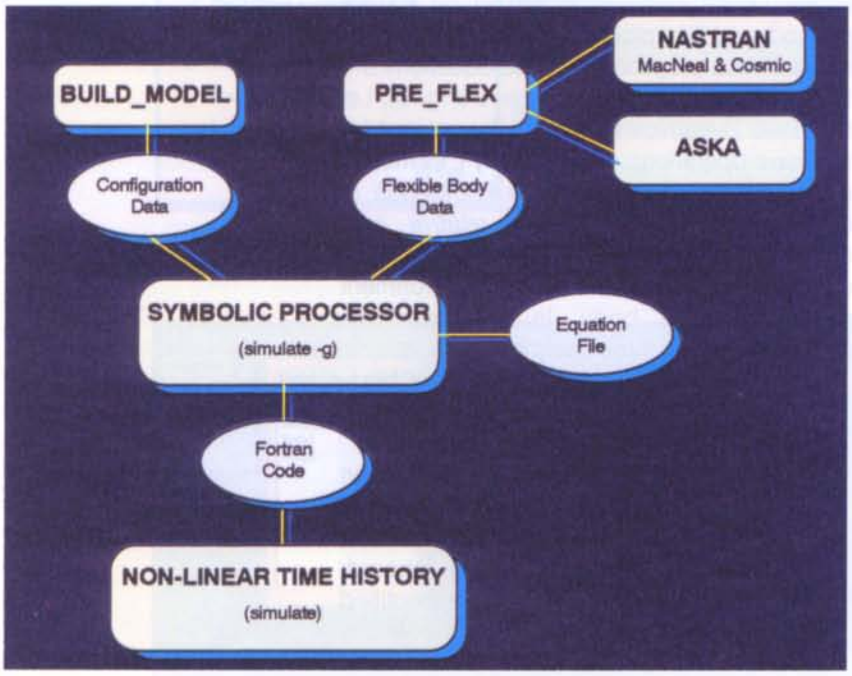


Figure 6. Context diagram

A schematic of the symbolic processing and simulation modules, along with their relationship with the DCAP package, is shown in Figure 6. They receive their input from three sources:
- a configuration data file which describes the multi-body system being simulated, its topology and properties
- a flexible-body data set that contains data relating to the flexibility properties of each flexible body in the system
- an equation file containing the templates of the equations of motion of a generic multi-body system.

The output from the symbolic processor is a set of FORTRAN files containing the implementation of the specific set of equations of motion that are applicable to the multi-body configuration defined. This source code is then compiled and linked with the simulation library to generate the executable module.

Validation and testing

The latest release of DCAP (Release 7) has been extensively tested through a dedicated testing campaign carried out by an independent team at Alenia Spazio. In addition, during the last phase of DCAP's development (1991 – 1994), the current implementation of the multi-body dynamics was compared extensively with similar packages like Treetops, SSIM (Space Station SIMulation), and against exact analytical solutions implemented in tools like MATLAB.

During 1993, DCAP's performance was assessed against those of other software products for the non-real-time simulation of robotic manipulators of the HERA (Hermes Robotic Arm) type. The testing and evaluation were carried out by Fokker Space Systems in the framework of the HERA Simulation Facility activities. The evaluation was based on multiple criteria, including: functional model and interface requirements coverage, run performance, accuracy, test case results, and cost. DCAP was the only software package that ran all of the test cases successfully, with perfect matching of energy and momentum balances. It also offered the best cost/benefits ratio.

Finally, as part of the final acceptance exercise, an executable DCAP tape was distributed by the Agency to a number of space industries and universities in order to collect expert feedback and comments.

Applications

DCAP software has been available to the European space community since the end of 1983 and has been used extensively within the Agency for satellite simulations (e.g. for Olympus, ERS-1), pilot studies, and checking of contractors' work. Since 1991, the dynamics formulation, as implemented in Release 7, has been successfully applied in technological studies as well as projects, in the field of spacecraft and robotic-system dynamic simulation, mechanism analysis, and control performance verification. Some of these applications are described below in a little more detail to demonstrate the package's flexibility in terms of modelling capability and simulation fidelity.

Microgravity dynamic disturbance study

The goals of this study were to assess the environmental disturbances to microgravity experiments induced on flexible large platforms and to define a methodology for their evaluation. In this context, DCAP has been used to:

- compute frequency responses between source disturbance points and target microgravity locations
- verify acceleration levels with time-domain responses
- analyse the effects induced by antenna pointing mechanisms and control
- implement a six degree-of-freedom microgravity isolation mount model to reduce the acceleration spectra at specific payload locations below Space Staion/Columbus specifications.

The analysis was carried on a full flexible spacecraft, modelled as a five-body system (core body, two solar arrays, antenna mast and a payload platform). Direct interfacing to NASTRAN finite-element data was used for component-body characterisation:

- Model characteristics
  532 grid-point core body
  80 grid points for each solar panel
  20 grid points antenna mast
  rigid payload platform
- Craig-Bampton component-mode synthesis redundant constraint modes and fixed-interface normal modes
  91 flexible modes retained (25 + 27*2 + 12)
  14 rigid degrees of freedom (6 d.o.f core body, azimuth and elevation antenna freedoms, 6 d.o.f isolation mount)
- Perfect overlapping of DCAP frequency response w.r.t. NASTRAN up to the 30 Hz range
- Unique ability to include mechanisms in flexible-body chains (NASTRAN limitation with mechanisms and related control).

Drag-free satellite control study

This study was aimed at addressing the drag-free-control approach for mission scenarios like Aristoteles and STEP. The use of DCAP was particularly oriented to the verification of the STEP satellite's drag-free design performance by means of a simulation combining the complete model of the satellite configuration and the control laws as defined during the study's evolution. To this end, the spacecraft was modelled as a three-body structure: a central rigid body, one flexible solar array, and a third rigid body connected by a spring-dashpot device to account for the helium sloshing.

Special attention was paid to the definition of the sensor, actuator and control-law modelling to reflect the design and the approach adopted by Matra Marconi Space (MMS), responsible for this task within the study. In particular, the models of the actual sensors and actuators were accommodated in a 'User Continuous Controller'. The attitude-control laws were implemented in a 'User Discrete Controller' that incorporated the FORTRAN routines defined by MMS for the attitude estimation and control schemes and the thruster firing logic. Finally, the drag-free control laws for translation were introduced as a 'Discrete Matrix Controller'.

Based on this model, simulations spanning 20 orbits (about 105 seconds) were run with the discrete controllers sampled at 10 Hz and an integration step of 5×10^{-3} seconds to check the transient actuator dynamics between controller updates. The synthesis of the response power spectra was performed using the built-in harmonic analysis and Fast Fourier Transform (FFT) computation. In these runs, 1 second of CPU time on an SGI Indigo R4000 work station was required to solve 5 seconds of real system time.

Atmospheric Re-entry Demonstrator (ARD)

This application was related to the study of the dynamic behaviour of the ARD re-entry capsule under parachute loadings, the analyses being performed within the framework of the ARD/DRS Programme. The DCAP software was used to model and analyse:

- the back-cover extraction driven by the pilot parachute
- the drogue-parachute stabilisation phase
- the main parachute cluster descent.

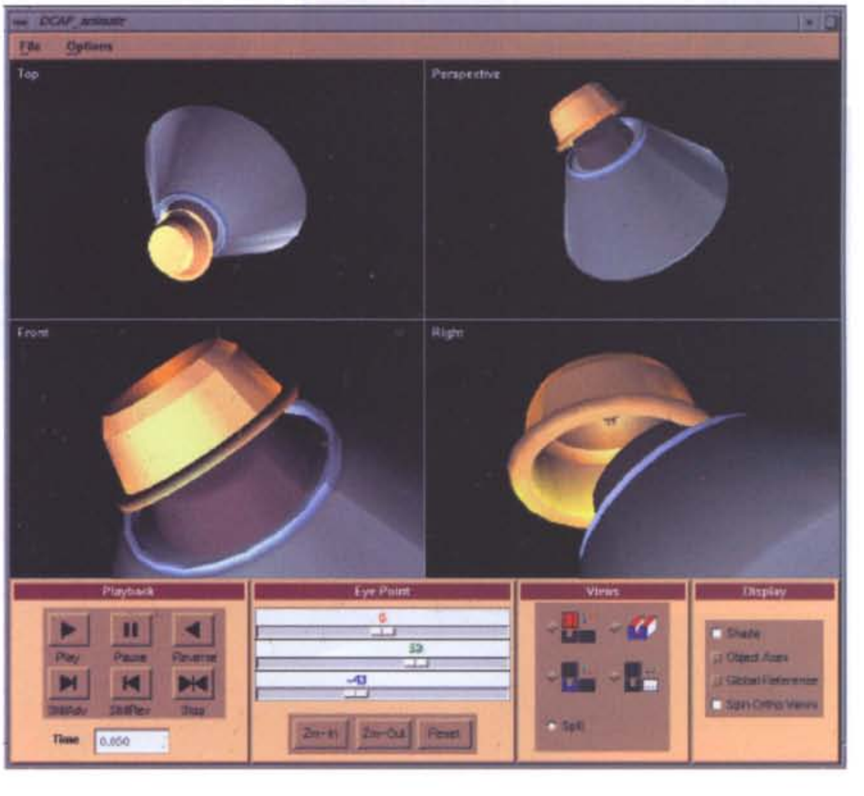


Figure 7. ARD example

To perform these analyses, both the built-in features of DCAP and its ability to incorporate user-defined software were extensively exploited. In particular, the handling of closed-loop topology and the non-linear hard-stop devices allowed multiple contacts between the back cover's corner and the capsule itself during the separation phase to be studied. A special set of user-defined subroutines was developed to support the simulation of the stabilisation and descent phases. This allowed extensive study of the system's behaviour, including:

- analysis of the 3D capsule aerodynamics at low altitudes with aerodynamic-coefficient interpolation with respect to the angle of attack and Mach number
- modelling of the flexible suspension lines, parachute bridles and riser, accounting for non-linear stiffness and loss of tension (slack condition)
- simulation of parachute reefing stages, with trapped air masses under canopies.

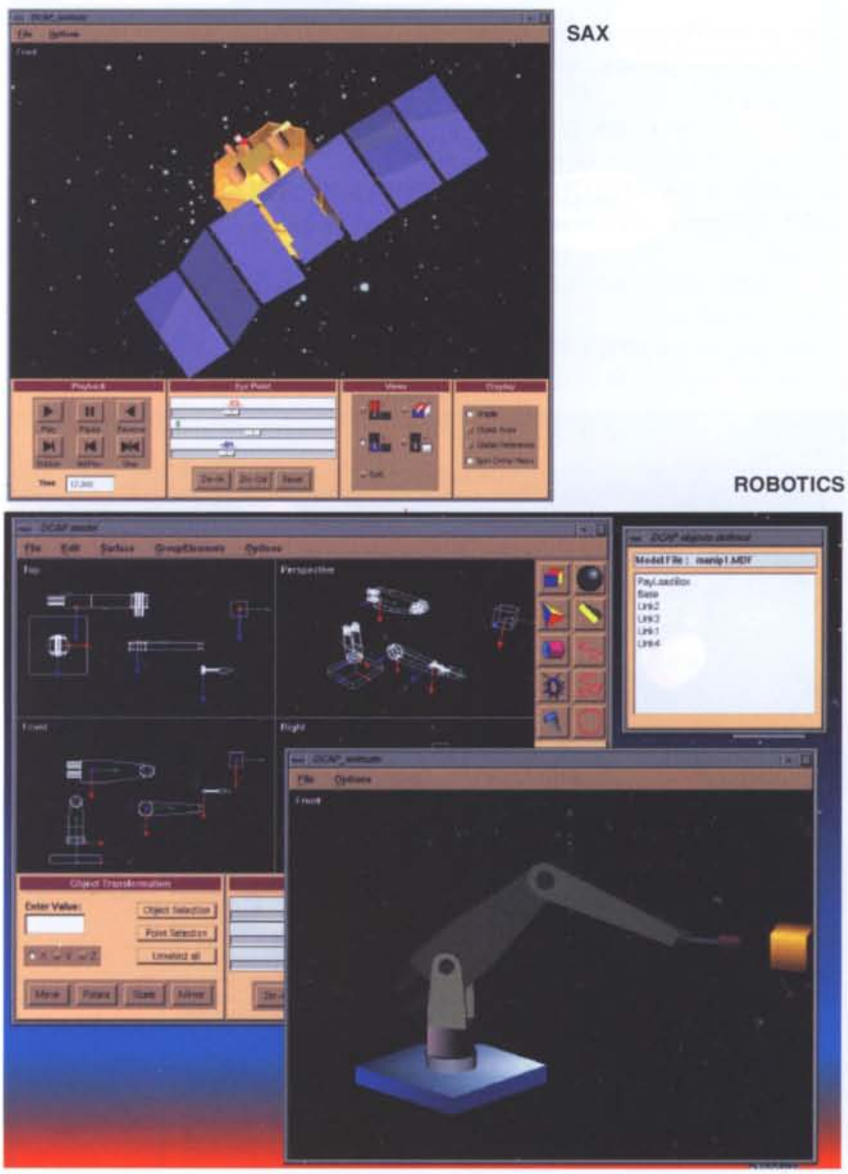


Figure 8. SAX and ROBOTICS examples

The analysis of the results benefitted substantially from the use of the DCAP graphical modelling and animation tools, particularly the contact determination during the separation phase. An accurate validation will be possible against the physical data expected from the ARD balloon-borne flight-test scheduled for July 1996.

SAX satellite

DCAP was used extensively during the design and development of the SAX X-ray astronomy satellite, developed by Alenia Spazio for the Italian Space Agency (ASI), for:

- analysis of deployment manoeuvres and shock loadings on the spacecraft's Advanced Rigid Arrays (ARAs)
- modelling and simulation of deployment springs, synchronisation cables and locking mechanisms
- external-disturbance evaluation and momentum-wheel management
- analysis of internal and external torques induced by the orbital environment, structural flexibility, fuel sloshing and locking mechanisms
- validation of the SAX real-time dynamic simulator.

The telemetry data collected during the first months of the SAX satellite's operation have shown very good agreement with the DCAP predictions for the solar-array deployment manoeuvres.

Robotics

The non-linear dynamics module of DCAP was used for an Autonomous Robot Control Simulation (ARCS-1) as part of an ESA study for the development of a prototype of a robot simulator. It was integrated within the overall architecture used to perform the simulation of various robotics tasks, including the 'grasp' and 'release' of objects, and to run in connection with the robot controller simulator.

DCAP was also used in the Automated Manipulation and Transportation System (AMTS) study for modelling the manipulator arm and for verifying the accelerations induced in the Attached Pressurised Module (APM) by the arm's manoeuvring.

Conclusion

The structure and the features of the DCAP package have been presented along with a number of selected applications. From this material it can be concluded that DCAP provides an outstanding and generic capability for modelling complex multibody systems and for analysis and simulation of their dynamic behaviour.

Current and Future Techniques for Spacecraft Thermal Control

1. Design drivers and current technologies

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The first part of this article reviews the design drivers and the technologies currently used for spacecraft thermal control. The second part focussing on future technology developments in thermal control will appear in a later issue of the Bulletin.

Why the need for thermal control?
The need for a Thermal Control System (TCS) is dictated by the technological/functional limitations and reliability requirements of all equipment used onboard a spacecraft and, in the case of manned missions, by the need to provide the crew with a suitable living/working environment. Almost all sophisticated equipment has specified temperature ranges in which it will function correctly. The role of the TCS is therefore to maintain the temperature and temperature stability of every item onboard the spacecraft within those predefined limits during all mission phases and thereby using a minimum of spacecraft resources.

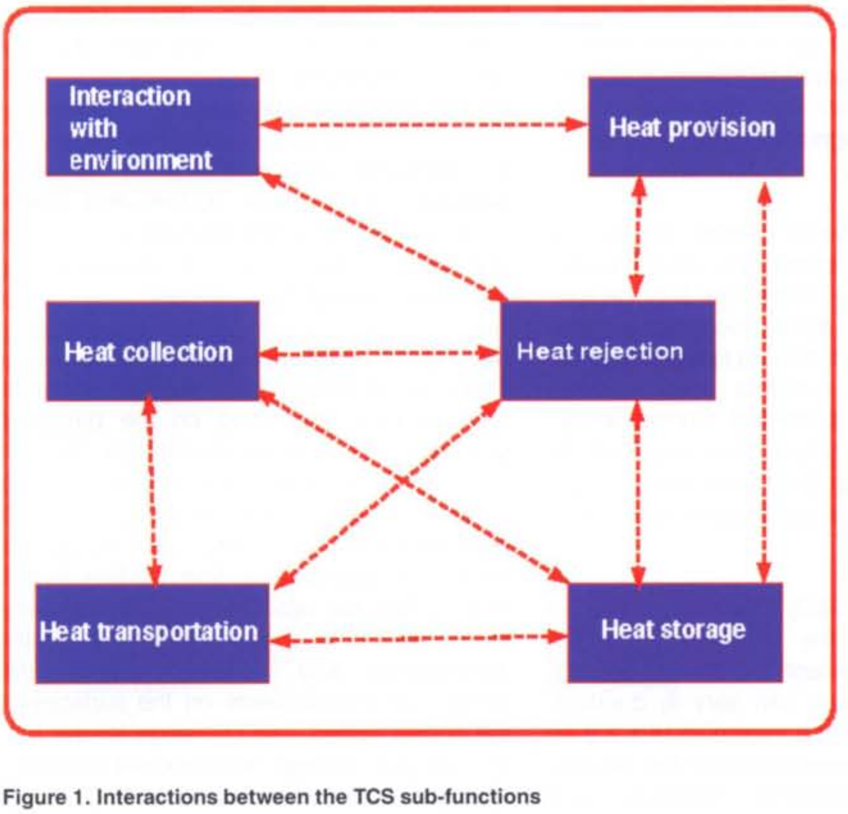


Figure 1. Interactions between the TCS sub-functions

The overall thermal-control function can be split into several different sub-functions (Fig. 1).

Interaction with the environment
The external surfaces of a spacecraft may either need protection from the local environment or improved interaction with it, involving:
- the reduction or increase of absorbed environmental fluxes
- the reduction or increase of heat losses to the environment.

Heat provision and storage
In some cases, to reach or maintain the desired temperature level, heat has to be provided and/or a suitable heat-storage capability has to be foreseen.

Heat collection
In many cases, dissipated heat has to be removed from the equipment in which it is generated to avoid an undesirable increase in the unit's, and/or the spacecraft's temperature.

Heat transport
Generally speaking, it is not possible to reject the heat directly where it is generated, and appropriate means have to be used to transport it from the collection device to the radiating device.

Heat rejection
The heat collected and transported has to be rejected at an appropriate temperature to a heat sink, which is usually the surrounding space environment. The rejection temperature depends on the amount of heat involved, the temperature to be controlled and the temperature of the environment into which the device radiates the heat.

The design drivers
The major parameters driving the TCS design are:
- the environment in which the spacecraft has to operate
- the total amount of heat dissipated on board the spacecraft

- the distribution of the thermal dissipation inside the spacecraft
- the temperature requirements of the various equipment items
- the configuration of the spacecraft, and its reliability/verification requirements.

About the environment

For all spacecraft, the incoming energy from the Sun and the heat radiated to deep space are usually the major environmental interactions. Depending, however, on the spacecraft's orbit and attitude, other parameters can have an important influence on the thermal-control design. For example, the type of attitude stabilisation used can affect the TCS design. In general, spin stabilisation is more benign, as the rotation induces an averaging of the environmental flux input. Three-axis stabilised spacecraft need greater protection against short-term variations in energy input from the Sun or Earth.

Low Earth Orbit (LEO)

This orbit is frequently used by spacecraft that monitor or measure the characteristics of the Earth and its surrounding environment (Earth observation, geodesy, etc.), and by unmanned and manned space laboratories (Eureca, the International Space Station, etc.). The orbit's proximity to the Earth has a great influence on the TCS needs, with the Earth's infrared emission and albedo playing a very important role, as well as the relatively short orbital period (less than 2 h) and long eclipse duration (up to a third of the time). Small instruments or spacecraft appendages such as solar panels that have low thermal inertias can be seriously affected by this continuously changing environment and may require very specific thermal design solutions.

Ascent and re-entry

For space transportation systems, the ascent to and re-entry from operational orbit (usually, LEO) can introduce additional TCS design constraints. During these two phases, the environment is often too warm to reject heat by radiation, and the radiators used in orbit are often closed or protected. Consequently, alternative heat sinks (e.g. flash evaporators) or special TCS designs providing a high thermal inertia have to be foreseen to manage these heat loads.

Geostationary orbit (GEO)

In this 24 h orbit, the Earth's influence is almost negligible except for the shadowing during eclipses, which can vary in duration from zero at solstice to a maximum of 1.2 h at equinox. Long eclipses influence the design of both the spacecraft's insulation and heating systems. The seasonal variations in the direction and intensity of the solar input have a great impact on the design, complicating the heat transport by the need to convey most of the dissipated heat to the radiator in shadow, and the heat-rejection systems via the increased radiator area needed. Almost all telecommunications and many meteorological satellites are in this type of orbit.

Highly Eccentric Orbits (HEO)

These orbits can have a wide range of apogee and perigee altitudes, depending on the particular mission. Generally, they are used for astronomy observatories (Exosat, IRAS, ISO, etc.), and the TCS design requirements depend on the spacecraft's orbital period, the number and duration of the eclipses, the relative attitude of Earth, Sun and spacecraft, the type of instruments onboard and their individual temperature requirements, etc.

Special orbits

Missions designed for the long-term observation of particular phenomena need a constant, stable environment and therefore tend to make use of stable orbits needing very low station-keeping resources, far away from any celestial body, e.g. around a Lagrangian point. Scientific spacecraft such as SOHO and the future scientific mission COBRAS-SAMBA, are typical of this class of mission. The spacecraft are Sun-pointing and therefore have one side constantly illuminated and all other faces exposed to deep space. Consequently, the TCS design can be optimised fairly easily, unless there are very special temperature requirements or there is insufficient electrical power for the heaters.

In particular, spacecraft with cryogenic payloads benefit from a low and stable temperature environment in terms of mass (if cryostats are used) or power and complexity (for satellites using cryo-coolers).

Deep space and planetary exploration

This class of mission includes many different sub-scenarios depending on the particular celestial body or target exploration zone. In general, the common features are a long mission duration and the need to cope with extreme thermal conditions, such as cruises either close to or far away from the Sun (from 1 to 4 – 5 AU), low orbiting of very cold or very hot celestial bodies, descents through hostile atmospheres, and survival in the extreme (dusty, icy) environments on the surfaces of the bodies visited. The challenge for the TCS is to provide enough heat-rejection capability during the hot operating phases and yet still survive the cold inactive ones. The major problem is often the provision of the power/energy required for that survival phase.

About the heat dissipation and its distribution

Two factors are important in this context for the TCS design, the absolute value of the heat to be dissipated and its distribution onboard the spacecraft, i.e. the power density. The first value has a big impact on the heat-rejection function (the dimensions of the radiator area increase with increasing power), while the power density defines the heat collection and transport functions (a high power density calls for highly efficient heat removal). Typical installed powers for various kinds of spacecraft are compared in Table 1.

Two conflicting requirements can be detected in terms of power utilisation:

- the increase in the installed power on multi-purpose, multi-band telecommunications satellites, and therefore the need for larger and more efficient heat-rejection systems
- the decrease in the dimensions of other classes of spacecraft and equipment due to the miniaturisation of the electronics. On the one hand this implies a reduction in the overall amount of power being used onboard, but on the other there is the risk that the power density increases, thereby generating a different class of problem.

Another very important factor is the duty cycle. The best solution would be power dissipation which compensates for the change in environmental fluxes (e.g. maximum power dissipation during eclipses!), so as to have an almost constant global heat input to the spacecraft. Given the present, near- and probably medium-term power generation methods, the reality is exactly the opposite: the maximum power dissipation occurs together with the maximum environmental fluxes. This forces the TCS design towards an over-dimensioning of the heat transport and rejection equipment to cope with the concurrent peaks. In turn, this over-dimensioning causes an increase in the complexity of the design and the need for more resources during the cold phases of the mission.

This introduces the third mutual interaction between the power subsystem and the TCS, namely the availability of power during cold mission phases for the heat-provision function. During those phases, power is generally provided by batteries and is therefore limited. This limitation can create further complexity in the TCS design.

About the temperature requirements

This factor is largely related to the technology of the spacecraft equipment. As already mentioned, it is the TCS's task to keep all equipment items working within their allowable temperature ranges, which in turn depend on the internal design, the components used and, last but not least, the required reliability. This applies in particular to electronic and electro-mechanical equipment, the design of which is often too similar to that of its 'terrestrial' counterpart, which has to work in a much more benign environment (air is an added value for TCS!). Improved thermal designs, in combination with better definition of the allowable temperature ranges, could save projects both time and money in the long run.

Three relevant temperature bands can be defined:

- cryogenic range: all temperatures lower than 120 K
- conventional range: temperatures between 120 and 420 K
- high-temperature range: all temperatures higher than 420 K.

We will concentrate here on the 'conventional range', articles relating to the other two ranges already having been published in past editions of the ESA Bulletin (e.g. No. 75, August 1993 and No. 80, November 1994).

Table 1

Mission	Orbit	Attitude	Installed Power (W) min.	Installed Power (W) max.
Science:				
– astronomy	HEO, Fixed point	Sun pointing (mostly)		
– deep space	Various transfer orbits	Sun or planet pointing	200	1 500
Telecommunication	GEO	Earth pointing	500	5 000
Earth Observation	LEO	Earth pointing	500	5 000
Meteorology	GEO	Earth pointing	200	1 500
Manned Vehicles	Transfer + LEO	Various	1000	10 000
Manned Stations	LEO	Sun pointing	3000	30 000

Within our conventional range, different sub-ranges can be identified according to the various equipment requirements. Classical examples include:
- the batteries, which are the 'worst' subsystem equipment since they can have a wide range of power dissipations and, at the same time, always have a very narrow operating (and non-operating!) temperature range (typically between −5 and +20°C)
- the propulsion subsystems, usually limited for safety reasons to the range 5 to 40°C even if, depending on the particular system, a wider range may be acceptable
- the generic electronics, with an average operating range between -20 and +70°C.

Nonelectronic items can have a wide range of temperature requirements, most of which are of a functional nature, e.g. limitation of thermal noise in sensors. Some extreme examples are shown in Table 2.

Temperature uniformity and stability can have an even greater impact on the TCS design than the absolute temperature values themselves. The former can be expressed either as the maximum allowable temperature difference between two adjacent parts, or as the maximum temperature gradient in continuous bodies. The temperature stability refers to the maximum allowable variation in the temperature of a specific item over time. The ability to cope with these requirements depends on the environment and power-duty-cycle design drivers and on the actual spacecraft configuration.

Great care has to be taken to discriminate between the 'nice to have' and the truly mandatory requirements, as sometimes even few degrees (or a few tenths for stability) can make the difference between a feasible and an unfeasible system or, at the very least, between an affordable and a very expensive system.

About the spacecraft configuration, reliability and verification requirements

One of the major problems of TCS design is that the spacecraft configuration is usually defined based on the physical accommodation of the various payload and basic subsystem (propulsion, solar arrays, etc.) elements. Only when the physical configuration is virtually frozen is the TCS designer brought in to assess whether all of the temperature requirements can be met. Should this not be the case, a great deal of time (and money) then has to be spent in trying to re-accommodate equipment and find ad-hoc solutions, which are never resource-efficient. Concurrent engineering should be applied more often at all levels, from the equipment to the spacecraft design, to try to overcome these not infrequent problems.

Reliability affects the TCS both directly (the TCS function has its own requirement) and indirectly through the equipment temperature requirements. The greatest impact is on the heat-provision, transportation and rejection functions. For manned vehicles, for instance, the reliability required for the cooling loops can cause an enormous increase in the complexity and mass of the TCS.

Verification, and in particular testing, requirements have too often been the cause of an efficient TCS design being rejected. The reluctance to use heat pipes due to the complications introduced into the thermal system tests (see section on heat-transport systems) is a classical example. As already demonstrated by many commercial spacecraft, a proper combination of testing at component and system level with analytical correlation techniques can solve such problems, resulting in a simpler and more efficient temperature control system.

Importance of parameters

The various design drivers have different impacts on the various TCS functions and on the mass, complexity and cost of their respective design solutions. Table 3 gives an indication of the relationships between the design drivers examined and each TCS function ('o' means little or no impact, while an 'x' indicates a growing level of importance; M = mass; CX = complexity; CT = cost).

Table 2

Item	Operating Temperatures (°C)		Non-oper./Storage Temperatures (°C)		Uniformity (°C/m)	Stability (°C/min)
	Min.	Max.	Min.	Max.		
Video-Camera CCD	−150	−100	–	–	–	±0.5
Laser Thermal I/F	5	10	5	10	±0.5	±0.1
Fluid-Physics Samples	5	90	5	40	±0.1	±0.01
Life-Science Samples	4	38	−80	−80		±1.0

Table 3

	Environment Protection			Heat Prov. and Storage			Heat Collection			Heat Transport			Heat Rejection		
Design Drivers	M	CX	CT	M	CX	CT	M	CX	CT	M	CX	CT	M	CX	CT
Environment	xx	xx	xx	x	xx	x	o	o	o	o	o	o	xxx	xx	xx
Heat Dissipation															
– absolute	o	o	o	o	o	o	xx	x	xx	xx	x	xx	xxx	xxx	xxx
– density	o	o	o	o	o	o	xx	xxx	xxx	xx	x	xx	x	x	x
Temperature															
– level	x	x	x	xx	xx	x	x	x	x	x	xx	xx	xxx	x	xx
– stability	x	x	x	xx	xxx	xx	xx	xx	xx	xx	xx	xx	x	x	x
– uniformity	x	x	x	xx	xxx	xx	xx	xx	xx	xx	xx	xx	x	x	x
Reliability	o	o	o	x	xxx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
Configuration	x	x	x	x	x	x	x	xxx	x	xx	xx	xx	xx	xx	xx
Assembly, Integration	x	x	x	xx	x	x	xx	x	x	xx	xx	xx	xx	x	x

Current techniques

Interaction with the external environment

Coatings

The easiest way to modify a surface's behaviour is to coat it with paint or a layer of other suitable material. All spacecraft make use of many different kinds of coatings, ranging from relatively simple-to-apply paints to more sophisticated chemically or physically produced conversion coatings. Coatings are characterised by their thermo-optical properties: absorptivity, emissivity, reflectivity and transparency.

The main disadvantages of coatings are the degradation caused by the operating environment and the contamination induced by ground handling or space operations, the absorptivity being the parameter most affected. Both the handling on the ground and the space environment tend to increase the initial absorptivity of a coating towards an end-of-life (EOL) value. The latter depends on the time spent in orbit, the relevant environment (particle fluxes, UV flux, etc.) and the orientation of the surface vis-a-vis the motion of the spacecraft.

A correct TCS design has to duly take into account all of these factors and use suitable begin-of-life (BOL) and EOL values.

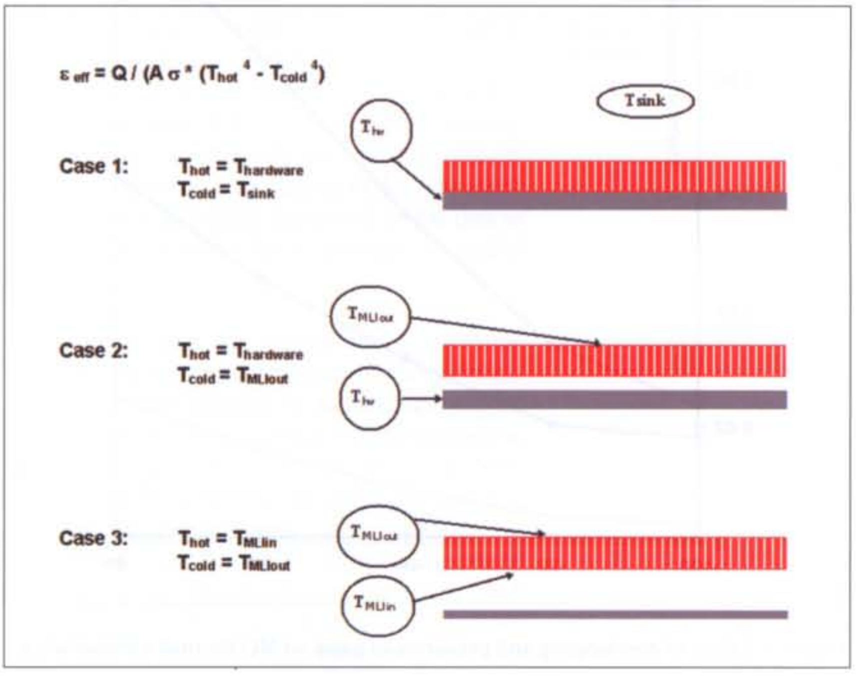
Multi-Layer Insulation (MLI)

When a simple coating is insufficient to avoid great heat losses or gains for a surface, multi-layer insulation can be used. It consists of a certain number of layers of plastic material (normally Mylar or Kapton) coated on one or both sides with a layer of metallic material to reduce the radiation, and separated by sheets of spacer material (e.g. Dacron net) to avoid direct contact between adjacent foils. The external foil coating depends on the particular application: it can be painted or metallised, or can even consist of a different material (e.g. glass-reinforced cloth).

MLI efficiency can be defined either in terms of the linear conductance through the blanket, or via the so-called 'effective emittance'. In the first case, the thermal flux can be calculated as the product of the given value times the temperature difference between the external layer and the hardware covered by the blanket. In the second case, it is calculated as a radiative heat exchange using the effective emittance (Fig. 2). This parameter has a very simple mathematical formulation, but it can have quite different physical meanings and the choice of definition depends on the modelling technique used.

The factors affecting the efficiency are the physical composition of the blanket (number of

Figure 2. Effective-emittance definition for various MLI layouts



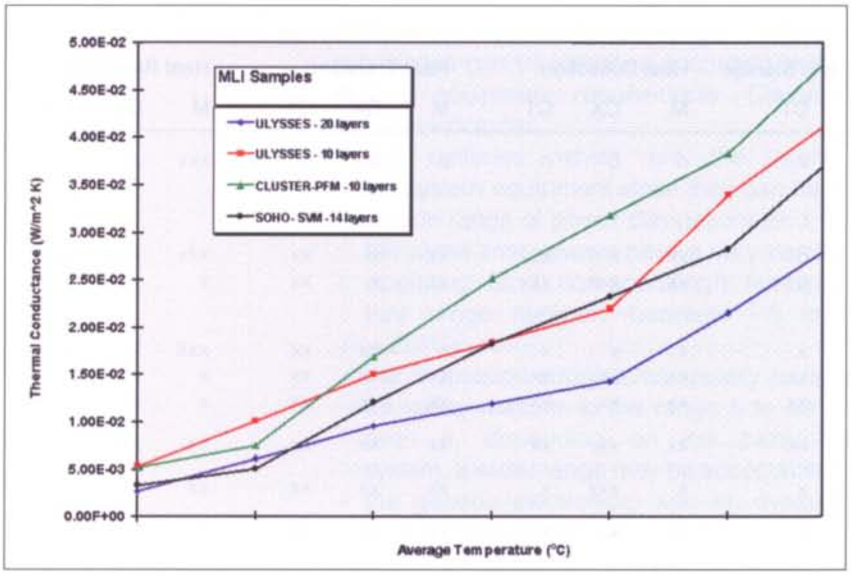


Figure 3. Thermal conductances of several MLI samples as a function of average temperature

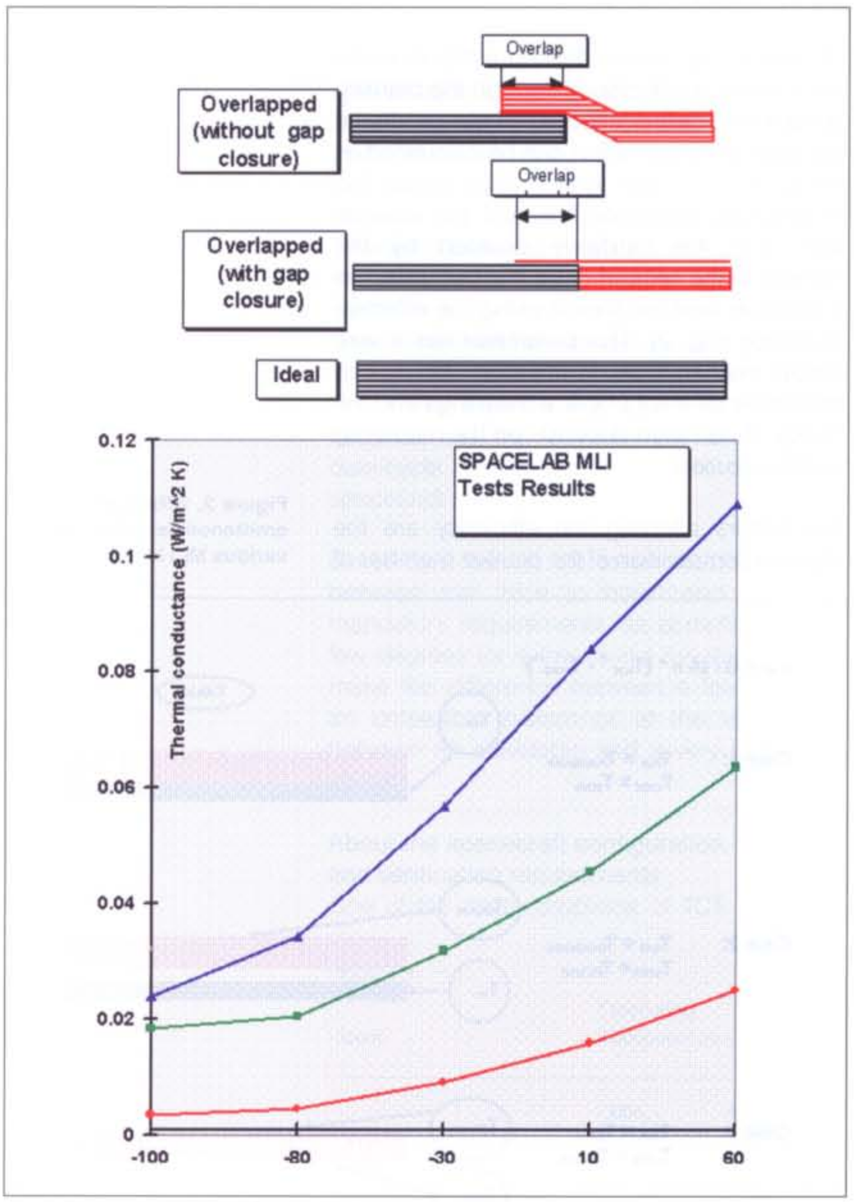


Figure 4. Effect of overlapping and presence of gaps on MLI thermal conductance

layers, type of coatings, etc.), the average blanket temperature (usually the arithmetic mean between the two outermost layers), the eventual presence of air or humidity within the layers, and the pressure between them. A very important factor is the way in which the blanket is applied to the spacecraft surface: a single piece of blanket covering a large surface is more efficient than a number of small blankets covering the same surface. A blanket suspended over a surface (case 3 of Fig. 2) is more efficient than one in direct contact with the surface (case 1 of Fig. 2).

Generally speaking, the MLI's efficiency is measured on relatively small samples, while the real efficiency of an MLI system is only known at the time of system-level thermal testing. Consequently, suitable safety factors have to be applied during the design phase.

Figure 3 shows the thermal conductance versus temperature for MLI samples measured at ESTEC for some recent ESA programmes. Figure 4 shows the thermal conductance versus the average temperature for samples and the real (with overlapping, seams, etc.) MLI (having the identical composition) as measured for Spacelab.

Louvres/shutters

A surface may only need to be protected during particular mission phases, whilst at other times it has to be free to radiate to deep space. Louvres can be used either to provide a heat sink during phases with Sun illumination, or to reduce the heat losses during cold (shadow) phases.

In the louvred radiator shown in Figure 5a, each blade is provided with a sensor/actuator element (e.g. a bi-metallic spring) which senses the temperature of the radiator baseplate and rotates the blade accordingly. The radiator can be blocked off completely when the temperature is lower (or higher for Sun louvres) than a pre-defined value, and exposed to various extents depending on the prevailing temperature levels. The accuracy of the temperature regulation depends on the physical characteristics of the louvre mechanism and is generally limited to ±5°C.

Louvres for use on top of radiators were developed in Europe in the early 1970s by ERNO and SNIAS (today DASA Aerospace and Aerospatiale, respectively), but they have not often been used aboard European spacecraft.

A shutter (Fig. 5 b) consists of a thin metallic plate (or blanket), which can be slid over a surface (usually by an electric motor) to vary the exposed radiator area in an almost continuous manner from zero to maximum exposure. The advantages compared with louvres are a greater effective emissivity when the shutter is completely open (no or very limited multi-reflection effects) and a better insulation efficiency when completely closed. A thermal shutter of this type was used on ESA's Giotto spacecraft.

The advantages of louvres and shutters are greater adaptation to the environmental conditions and a reduction in the power and energy needed for heating during cold phases. The disadvantages are the mass and presence of the associated mechanisms, which can reduce the reliability of the TCS.

Heat provision

Electrical heaters

Electrical resistance heaters are the easiest means of providing heat to spacecraft equipment. The provision and storage functions are separated in that the former is performed by the TCS, while the latter is provided via the power subsystem.

The heaters can be powered continuously or, more usually, can be switched on and off according to the temperature of the controlled element. In the latter case, it is possible to have local control by thermostats or central control via a dedicated switching unit (the so-called thermal-control unit) or via the spacecraft Data Handling System (DHS). This implies the use of temperature sensors and data and command lines. Depending on the particular spacecraft configuration and temperature requirements, this heater monitoring and commanding system can become quite complex. The main disadvantages of heaters are therefore the need for electrical energy and either the complexity of the DHS or the reduced reliability if thermostats are used.

Electrical heaters are used on all spacecraft. In recent years, European heaters have been qualified according to the very stringent ESA specification for both single- and double-density designs (up to 200 Ohm/cm^2).

Radio-isotope heaters

Some planetary and exploratory missions to the periphery of the Solar System cannot rely on the Sun and batteries to produce and store electrical power for TCS purposes. Radio-isotope Heating Units (RHUs), based on plutonium, have then been used either to warm the spacecraft directly or to produce electricity via Radio-isotope Thermoelectric Generators (RTGs) to feed the heaters. There are currently no European manufacturers of RHUs or RTGs, but both the USA and Russia have developed and used these devices for their deep-space missions. Political as well as procurement problems will make the use of this type of RHU less and less acceptable in the future.

Heat storage

Phase Change Materials (PCM) offer the possibility to store thermal energy directly as latent heat of fusion or sublimation. The item to be controlled is linked to a vessel filled with a PCM. When the item is active, the PCM absorbs heat and melts or sublimates at a stable temperature; when the equipment is inactive the PCM can resolidify, releasing the relevant amount of heat. Usually, the melting PCMs can be used easily in reversible, closed systems, while the sublimating PCMs are used in open, non-reversible systems (i.e. the gas is released after the phase change to avoid over-pressure).

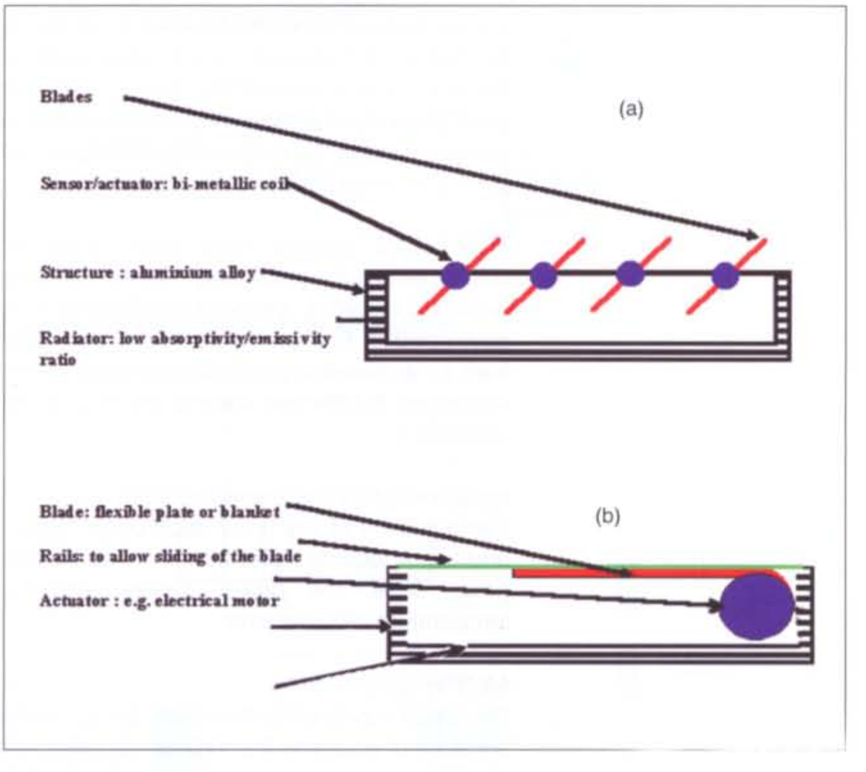


Figure 5. Louvre (a) and shutter (b) schematics

The most critical parameters are the temperature at which the phase change takes place, and the amount of heat absorbed or released during the change. The temperature ranges normally of interest are the near-zero range (−5 to +10 °C), or particular ranges for specific experiments, e.g. −80°C for life-science experiments. Other important parameters are the thermal conductivity and the density of the two phases; the former because of the need to transfer the heat efficiently inside the PCM, and the latter because the containing structures have to withstand the volumetric change of the PCM.

Two advantages of a PCM device are the stability of temperature control and the absence of moving parts. The heat-storage requirement is defined by the duty cycle for reversible systems, and by the total operating time for non-reversible (e.g. sublimating, boil-off PCMs) systems. Since the mass of the device is directly proportional to the heat-storage capability, it is difficult to use a PCM device without incurring a serious impact on the overall mass budget. Moreover, problems associated with the limited thermal conductivity of many PCMs make it necessary to use finned containers, which again increase the mass and volume of the devices. Another point of concern is the design of the container against leakage, for both safety (PCMs can be quite corrosive) and functional reasons.

PCM-based devices have been used on US spacecraft, including some Shuttle-launched missions. Various breadboards were developed in Europe in the 1970s but, apart from an application on Spacelab, there are no references to their use aboard other European spacecraft.

Heat collection and transportation

The selection of the most appropriate system and components depends on the overall power level, the power density and the temperature requirements.

Mechanical elements

The usual way to collect the heat dissipated by any item of equipment is through its baseplate and fixation elements (mounting feet). With increasing power dissipation, the complete baseplate has to be in contact with the spacecraft panel. The heat transferred then depends on such parameters as the interface pressure, the surface finish, the types of materials involved, etc., which are sometimes difficult to quantify (at design level) and control (during manufacture and integration). Ways of increasing the conductivity through the interface surfaces include the use of metallic or synthetic mats, or the application of thermal grease. This last solution has to be used with care because of the obvious potential contamination problems.

In some cases, a number of units are connected together to an intermediate solid panel called a 'doubler', which is usually made of aluminium. This doubler spreads the heat dissipation over a larger area, thereby providing an improvement in the temperature uniformity and an increase in the effective contact area to the heat-transport or heat-rejection device. It is convenient to locate redundant units or units operating with different duty cycles on the same doubler in order to use the heat dissipated by the operating units to maintain the others within limits without the need for additional heating power. The disadvantage of this simple solution is the mass of the doubler, which must be reasonably thick to achieve a good efficiency.

Braids of conductive material (e.g. copper) are sometimes used to connect heat-dissipating equipment to a 'remote' radiator. As the overall conductance is proportional to the braid's cross-section and inversely proportional to its length, this method can clearly only be used for short distances and very low heat loads. As an example, a copper rod weighing about 22 kg would be needed to transport 10 W over a distance of 1 m with a temperature difference of 10°. For comparison, a simple heat pipe (e.g. a stainless-steel/ammonia heat pipe with a diameter of 9.5 mm) provides a better performance (lower temperature difference) for a mass of 0.25 kg/m, i.e. about 100 times less. One advantage of the braid is its flexibility, which provides a certain degree of isolation from vibration and helps to avoid configuration problems.

Heat pipes

The heat pipe is a device that allows efficient transport of thermal energy. It typically consists of a sealed metal tube with a capillary structure on the inside, filled with a suitable working fluid. Heat is absorbed at one end by evaporation of the fluid, and released at the other by condensation of the vapour. The liquid is transported back to the evaporator by capillary forces.

The heat pipes most commonly used on spacecraft are an aluminium/ammonia type that allows optimal temperature control in the 0 – 40°C range. Since the quantity of heat transported by the pipe is defined by its design and dimensions, the equivalent thermal conductance is fixed, leading to the Constant Conductance Heat Pipe (CCHP in Fig. 6a).

There is also a special type of heat pipe known as a Variable Conductance Heat Pipe (VCHP, Fig. 6b). This device provides better temperature control when the equipment can either dissipate at different power levels, or the condenser is exposed to a varying environment. The amount of heat transferred is usually controlled by blocking part of the condenser area with an inert gas.

As the capillary forces are weaker than gravitational forces, heat pipes can only work in a gravity field if the evaporator and condenser are at the same level, or if the evaporator is below the condenser (so-called 'reflux mode'). Consequently, if a spacecraft has heat pipes located in different planes, it is not always possible to fully verify the complete thermal design with system-level testing alone. However, as already mentioned, this constraint can be overcome and should therefore not restrict the use of heat pipes, which offer great advantages.

Cooling loops

For greater power dissipation or more stringent temperature requirements, other heat collection and transportation systems can be used. Various kinds of fluid loops have been proposed and applied to cope with these situations.

In single-phase loops, the refrigerating liquid absorbs the heat from the heat-dissipating items (e.g. via a cold plate or a heat exchanger) by increasing its temperature, and transports it to the heat-rejecting device (heat exchanger or directly via a radiator) where the fluid is cooled down. A mechanical pump is essential to provide the hydraulic energy needed for this task (Fig. 7a).

The advantages of these systems lie in their flexibility and lack of sensitivity to their orientation and mechanical environment. The fluid flow rate can be easily regulated (e.g. via a variable-speed pump), allowing either a wide range of power duty cycles (a ratio of 1 to 10 is possible) and/or different levels of temperature accuracy, stability and uniformity. The temperature range can be adapted to the particular application by selecting an appropriate fluid. Since the fluid is circulated by the mechanical action of the pump, the system operates with the same efficiency on the ground, onboard a spacecraft, or during a descent on a celestial body. Disadvantages are the power needed to drive the pump and possible vibrations induced by the pump and fluid flows.

Single-phase fluid loops have been widely used since the early days of manned spaceflight. In Russia, they have also been used frequently for unmanned spacecraft; e.g. air loops have been used on Proton, liquid loops on high-power telecommunications spacecraft (in conjunction with deployable radiators), and combined liquid/air loops on retrievable low-orbit spacecraft (e.g. Foton). In Europe, they have been used on Spacelab and Eureca, and will be used in the future in

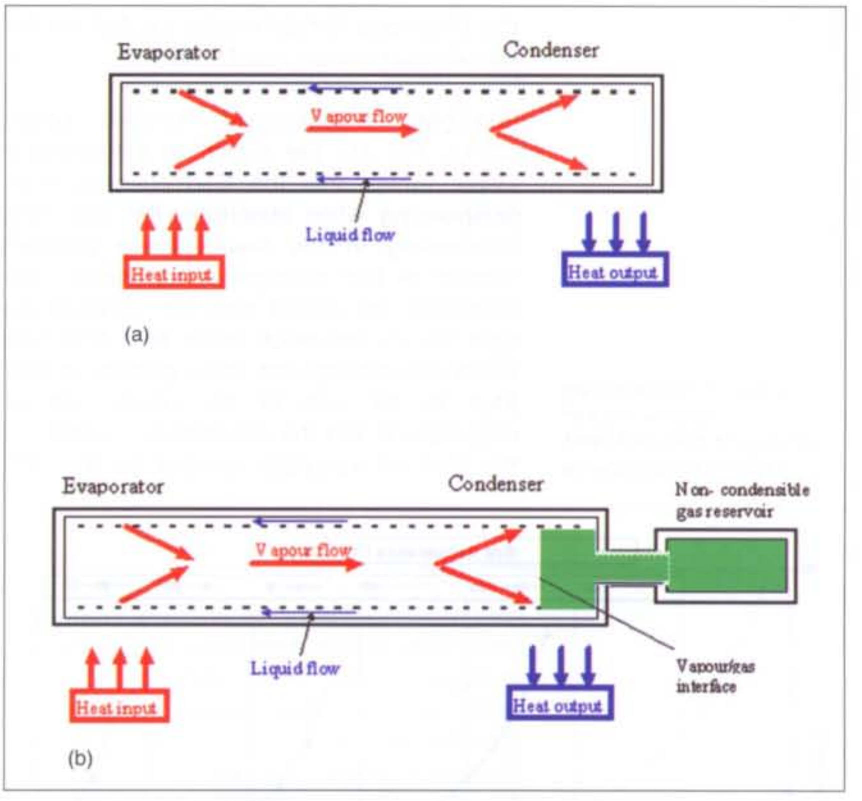


Figure 6. CCHP (a) and VCHP (b) schematics

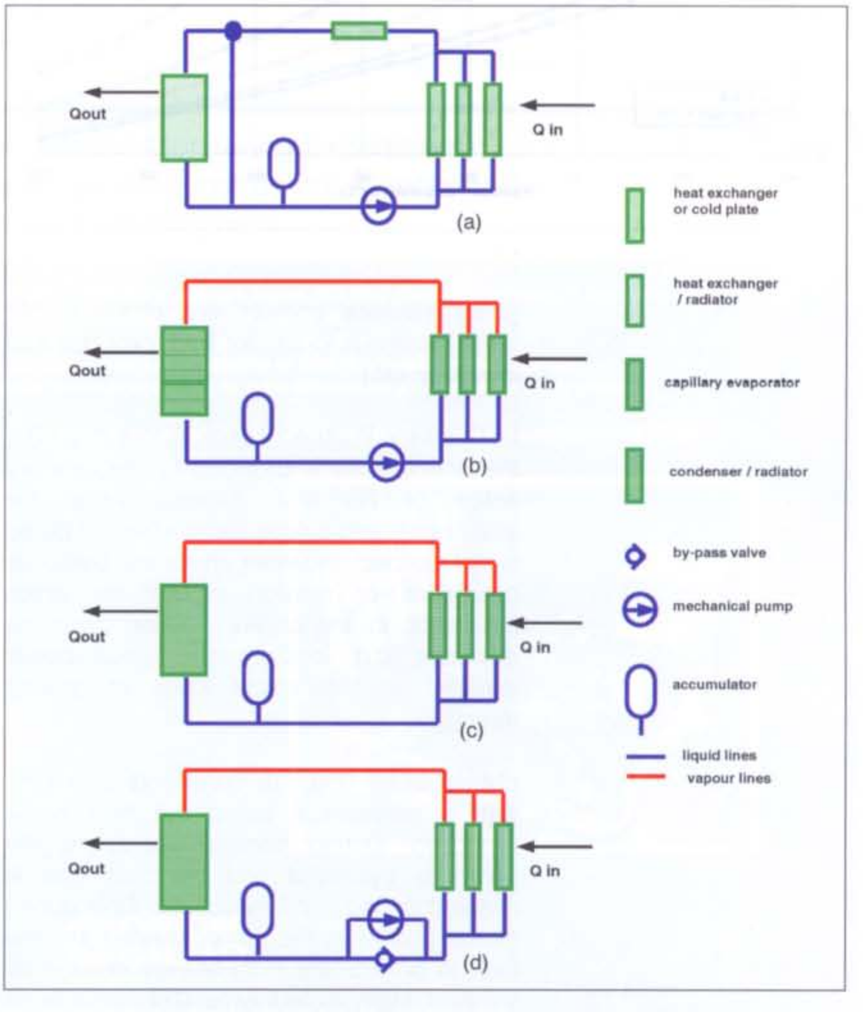


Figure 7. Schematics of cooling loops: (a) Single-phase loop. (b) Mechanically assisted two-phase loop. (c) Two-phase capillary loop. (d) Two-phase hybrid loop

the Columbus Orbital Facility as well as the Mini-Pressurised Logistic Module.

Two-phase Mechanically Pumped Loops (MPLs, Fig. 7b) are similar to single-phase loops, except that the fluid changes state (evaporating while absorbing the heat and condensing in the heat-rejecting devices) instead of just changing temperature. The advantage compared with the single-phase type lies in the much lower fluid flow rate needed to manage the same quantity of heat (due to the use of the latent heat of evaporation) and the associated reduction in the level of resources needed for the TCS (lower electrical consumption of the pump, lower mass due to smaller fluid lines and fluid inventory, etc.).

In Capillary Pumped Loops (CPLs: Fig. 7c), the driving force is provided by the capillary action of the wick material inside the evaporators and a separate mechanical pump is not needed. However, there are particular operations or mission phases for which assistance to the capillary action might be desirable (e.g. loop start-up, peak power loads, high mechanical loads or ground testing).

Hybrid loops (Fig. 7d) consisting of a CPL with a mechanical pump are now being proposed. During nominal operations, the pump is bypassed and the fluid flow is ensured by the capillary actions. Only during critical phases is the pump inserted into the loop to provide the extra energy needed by the fluid. Many experimental CPLs have been or are being flown to demonstrate the technology, which is currently baselined for several Earth-observation experiments, e.g. the European ATLID and the American EOS-AM.

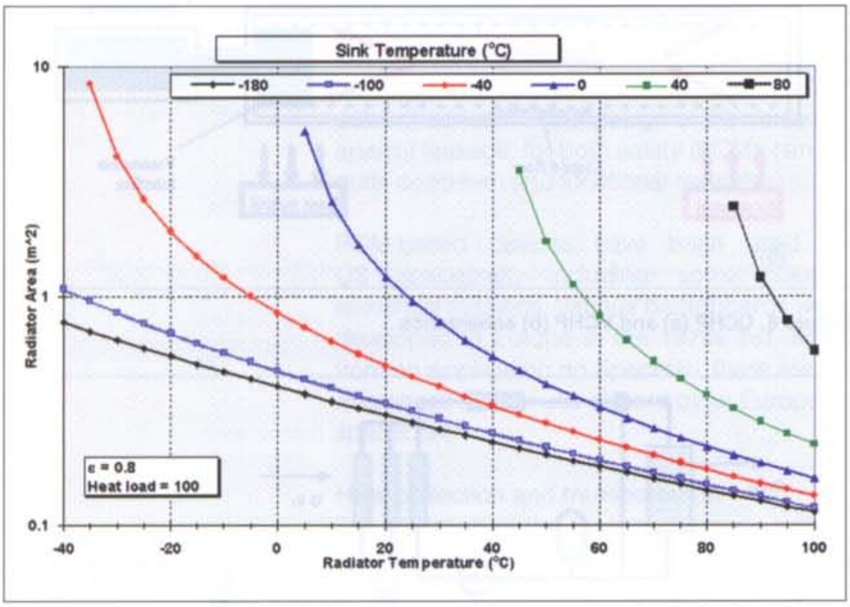


Figure 8. Influence on radiator area of environmental (sink) and radiator temperatures

Thermal joints

These are used to transfer heat from a fixed spacecraft element to any deployable/movable/rotating element (e.g. a radiator). Depending on the nature and extent of the allowable motion (single deployment, continuous rotation, etc.), the joint can either be very simple (the braid mentioned above for low heat loads) or considerably more complicated.

Flexible heat pipes have been proposed for single deployments, and rotating thermal joints (based on shape-memory alloys or gas pressure) for periodic rotation. They have yet to be flown on a European spacecraft.

Heat rejection

Radiators

A radiator is simply a (highly) conductive panel exposed to deep space and (normally) coated with a high-emissivity coating. Depending on the spacecraft's size and configuration, there can be central radiators to which all the heat dissipated on board is transferred, or multiple radiators each dedicated to a payload unit or group of payloads and/or subsystems.

The dissipating equipment can either be mounted directly on the radiator or connected to it via heat pipes or fluid loops. In the latter case, the heat pipes or fluid lines can either be fixed to the external faces of the radiator or directly embedded into its structure. The second solution is more efficient from the structural (mass-saving) and thermal viewpoints, but can also be less reliable due to the probability of micro-meteoroids impacting the radiator, and is more critical with regard to spacecraft integration activities.

The radiator's size depends on the power to be dissipated, the temperature of rejection (defined by the items to be controlled) and the temperature of the surrounding environment (Fig. 8). In most cases, the radiator is mounted on a spacecraft panel and therefore only radiates on one side. In the case of high and/or varying powers or changing environmental conditions, this configuration is not very efficient. A better solution is to use both faces of the radiator, but this implies the need for radiator deployment.

One way of coping with changing heat loads is to use louvres or shutters on top of the radiator, as discussed earlier.

Thermo-electric heat pumps

Heat pumps are reversible machines able to transfer thermal energy from lower temperature to higher temperature bodies using an additional source of energy. Only thermo-electric heat pumps have been used in space until now, the basic feature of which is the Peltier element, which results from the connection through a metallic tab of type-n and type-p semiconductor materials.

The efficiency of a Peltier element depends on its intrinsic characteristics (thermo-electric effect, thermal and electrical conductivity), the electrical current, the temperature to be controlled and the temperature of the heat sink. The overall performance of a thermo-electric heat pump is strictly related to the efficiency of the thermal coupling between the Peltier element tabs and the surfaces to be cooled or heated.

For low cooling/heating loads, the elements are bolted in between the baseplate of the controlled element and the heat sink. Thermal grease is usually applied at the interface to increase the joint's thermal efficiency. However, as the interface pressure cannot be high for mechanical reasons, this method is not adequate when high thermal performance is required (very strict temperature control and/or high cooling/heating loads). The preferred solution in this case is soldering of the elements to the heat sink.

The most efficient heat sinks are currently water heat exchangers. Good performance can also be obtained with air heat exchangers, at the expense of larger volumes and higher power consumptions (needed to drive the fans). In all other cases, the cooling/heating loads as well as the temperature difference between the cold and hot side have to be very small, otherwise the electrical power required becomes prohibitive.

Thermo-electric heat pumps are normally used for tight temperature control of low-power instruments (advantages being the absence of vibration and ease of installation) and of facilities used for microgravity experiments. Many systems have been developed and used for both manned (e.g. ESA's Biorack) and unmanned spacecraft (e.g. Biobox aboard Foton).

The ESA Initiative for Software Productivity Benchmarking and Effort Estimation

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The increasing general importance and scope of software applications is evident in almost every facet of modern life. There have been dramatic advances in computer technology and processing capability, with even the PCs to be found in many households having a processing capacity and range of sophisticated software which surpasses much of what was to be found in commerce and industry just a few years ago. It is therefore hardly surprising that in a leading-edge, high-technology activity like the space sector there has been a similarly marked increase in software applications and associated expenditure. This trend seems set to continue, in all probability with increasing momentum.

Introduction

Much of the commercial software available for general business use has been developed at enormous cost, but this is justified by the promise of widespread application and sales. There is, however, much software which is developed for very specific applications with special needs and characteristics. This is the case with most software development for the space sector, whether it be for on-board, in-space applications, which certainly have some unique characteristics, or whether it be for ground-segment applications for which the requirements may be different but the applications somewhat more extensive. There is also some specific software development for administrative purposes, but whilst the cost of such developments may be substantial, it is relatively insignificant compared with that of software development for the technical applications.

The increasing importance of software in the space sector

The proportion of the ESA budget spent on software-development contracts for its programmes has doubled in the last decade. The reasons for this growth are to be found in the predominance of the role played by the amount of processed information generated by each ESA spacecraft, and the ever-growing autonomy of these spacecraft (Fig. 1).

Today, expenditure on ground-segment software can represent some 40% of the related budget, whilst for the space segment expenditure on on-board software and ground test systems can represent in excess of 10% of that element's budget.

It is notoriously difficult to accurately predict software development costs, this being a problem both for those companies who actually carry out the development, and for customers such as the Agency who want to be sure that estimates of the effort required are credible and that prices are reasonable. A recent survey* has demonstrated a crucial challenge in this respect in that it was found that two-thirds of all major software projects have substantially overrun both their schedule and cost estimates.

Although more than 20 software cost-estimation models were already in existence as early as 1981, the survey revealed that in practice many software-development cost estimators still tend to rely rather more on their personal memory of the cost of similar projects than on use of other estimating processes. This approach can certainly not be relied upon, and the study concluded that this intuitive approach correlated positively with the percentage of large projects overrunning their estimates. Only the use of data for similar past projects based on documented facts, the use of simple arithmetic formulae, and the use of established standards, were found to lead to greater accuracy in software cost/effort estimates.

The need for a multi-company software metric database

From the beginning, the estimation of software development effort has never been easy. Firstly, the abstract nature of software makes it a difficult product to characterise, and design changes are often introduced into software before, during and after its pure code-production phase. Secondly, there are often

* Lederer & Prasad, *Nine Management Guidelines for Better Cost Estimating*, ACM, Vol. 33, No. 2.

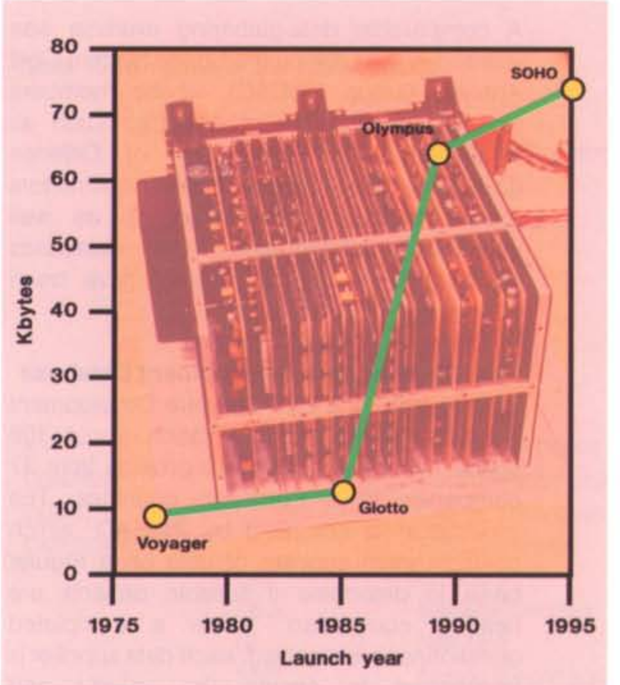
too few projects in process within a particular organisation to provide a good basis for estimating the cost of new developments. Lastly, software production has evolved in recent years from being something of a black art, into an engineering discipline in which there is a very rapid evolution of techniques. The momentum of change in this field therefore makes the process of basing new estimates on anything other than fairly recent developments very suspect. Consequently, the collection of software metrics is now viewed as the best basis for increasing software production efficiency and providing a rational means of measuring and estimating development costs. Such metrics allow the application of statistical-analysis techniques to generate the mathematical expressions needed as a basis for 'parametric cost models'.**

This article describes how ESA has organised a continuous gathering of historical data on software-development programmes from diverse sources, including sources outside the space sector. The latter are of interest because they provide the key to calculating the effect of specific characteristics of space software, such as the very high reliability required, the need to work first time, the need to be able to effect in-flight repairs and maintenance, and the specialised microprocessors on which it runs. This information has been analysed and the results distributed to the participating organisations, all of whom are interested in gaining a better understanding of the process and are seeking to be able to predict the effort required for their future projects more accurately.

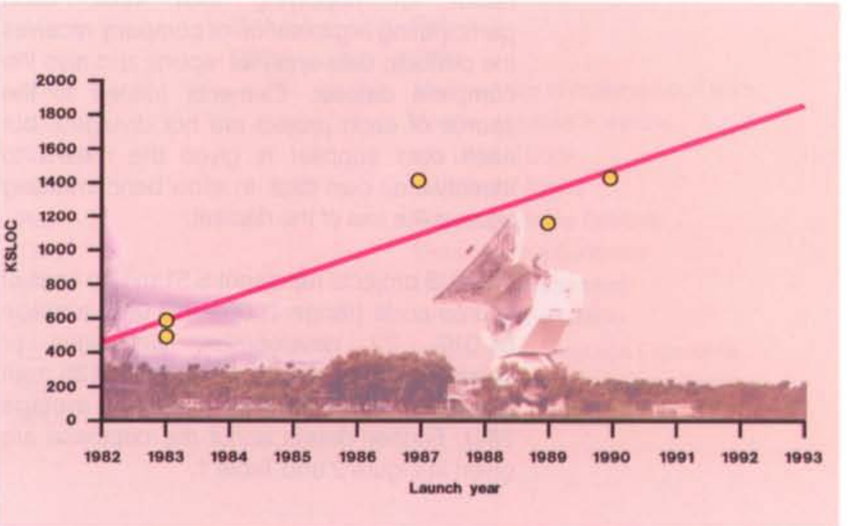
ESA/INSEAD collaboration

In 1988, the Cost Engineering Section of the ESA Cost Analysis Division, faced with the evaluation of proposals for large space programmes and the ever-increasing software-development element, began compiling a software metrics database focusing on effort and productivity measures. Industry was encouraged to participate in this initiative on the basis that by contributing 'productivity oriented' data they would receive in return the whole set of project case studies and a basic analysis of the data. Subsequently, the database was expanded to include military and industrial applications.

At the end of 1993, it was felt that this exercise should be intensified, which would necessitate additional administrative and management support. It was decided that INSEAD, as a leading international business school, would be an ideal partner with which to collaborate in this endeavour. Firstly, INSEAD would be seen by potential contributors as a neutral body, and not as a potential business competitor. Secondly, INSEAD was already conducting a large annual survey of European manufacturing industries, the survey itself involving techniques similar to the approach being followed for the software metrics exercise. Thirdly, researchers at INSEAD are involved in a number of other research projects designed to respond to the business and managerial challenges associated with achieving excellence in software, and there is thus some synergy between these activities and the ESA initiative. For its part, INSEAD was happy to participate in this task in order to gain a better understanding of the software-development process, with the aim of improving management practices in this area and determining performance benchmarks.



(a)



(b)

Figure 1a. Growth in spacecraft onboard data processing (PROM + RAM)
Courtesy of T. Vardenaga, ESA

Figure 1b. Growth in ground-segment software
Courtesy of J. Bui et al., US Institute for Defense

** Sets of mathematical equations describing the relationships between cost, schedule and measurable attributes of a system.

A comparable data-gathering exercise was initiated in the USA by the Space System Cost Analysis Group (SSCAG), whose members include US government agencies such as NASA and the Department of Defense (DOD), the largest space industry contractors (both American and European), as well as ESA. Subsequently, the databases on both sides of the Atlantic have been compared.

The ESA Software Development Database

By mid-1995, the ESA Software Development Database contained information about 108 space, military and industrial projects from 37 companies in 8 European countries. The information is compiled by INSEAD, which contacts each supplier of data on a regular basis to determine if suitable projects are nearing completion. When a completed questionnaire is received, each data supplier is telephoned to ensure the validity and comparability of questionnaire responses. In return for supplying their data, each participating organisation or company receives the periodic data-analysis reports and also the complete dataset. Elements related to the source of each project are not divulged, but each data supplier is given the means to identify their own data, to allow benchmarking against the rest of the dataset.

The 108 projects represent 5.51 million lines of source code (range 2000 – 413 000; average 51 010), 22 development languages or combinations of languages, and 30 125 man months of effort (range 7.8 – 4361; average 284). Further details about the database are given in Figure 2 and Table 1.

In the ESA database, 'KLOC', 'Effort' and 'Productivity' are defined as follows:

KLOC: The amount of non-blank, non-commented delivered kilo-lines of source code. As the software developed in some projects consists of reused code, adaptation adjustment factors are used to correct the size of the software.

Effort: The total effort is measured in man months and is defined as beginning with delivery of the specifications and ending at customer acceptance. The effort value covers all directly charged labour on the project for activities during this period. All effort data have been converted to man months based on 144 man hours per man month.

Productivity: In software-development terms, productivity is conventionally defined as delivered source lines of code per man month (LOC/MM). It is a measure of the output produced per unit of human effort.

Analysis of the ESA Software Development Database

Some general results of the productivity and effort estimation statistical analysis undertaken by the INSEAD research team are presented below. This study, whose details are available

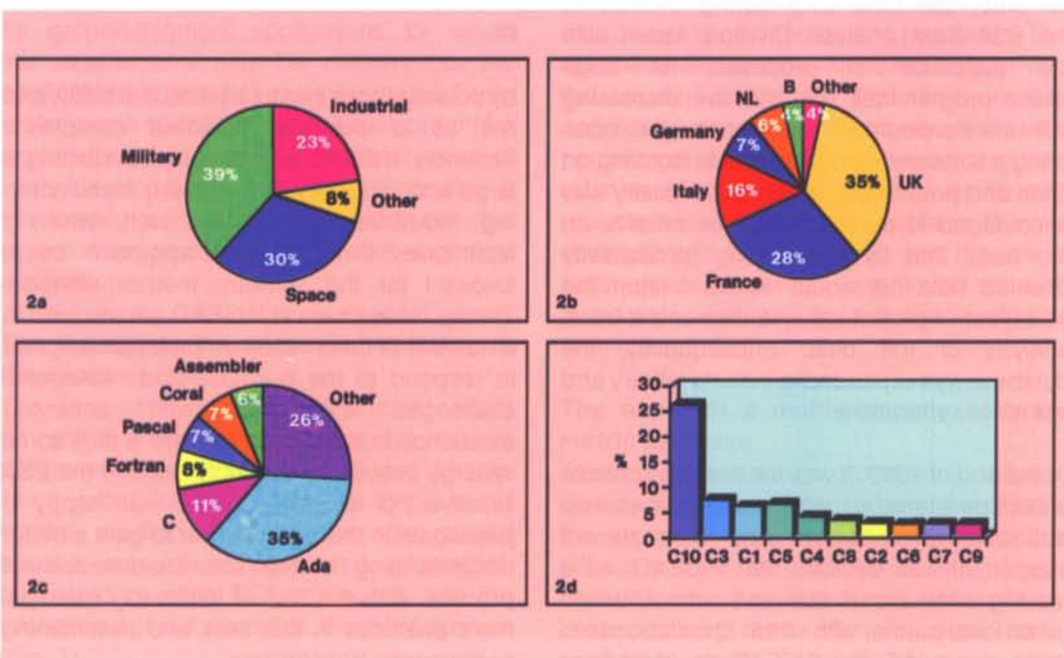


Figure 2a. Percentage of projects by main application environment

Figure 2b. Percentage of projects by country

Figure 2c. Percentage of projects by language

Figure 2d. Percentage of projects per company (ten largest data suppliers)

exclusively to the companies participating in the survey, is thought to be unique in that no other published research analysing such a large number of European non-MIS (Management Information System) applications can presently be identified.

Over the past years, many effort estimation models have been developed. However, because of differences in data collected, project types and environmental factors between software development sites, these models are generally only valid within the organisation in which they were developed, or after conducting extensive calibration exercises. One major obstacle to the transportability of these models appears to be a lack of understanding of the factors explaining the differences in productivity between projects. As there are literally hundreds of parameters that can affect software development effort, and as only a few of them may affect the productivity within a particular environment, it is important to analyse the accuracy of these effort estimation models based on the prior determination of the factors found to explain the productivity of projects in a given database. Furthermore, it is also important to determine whether effort estimation models based on the significant productivity factors of a multi-company database can be successfully used to make effort estimates within a specific company.

The first step in the analysis was to identify the factors that explain the productivity differences in the data. The factors considered were: company, country, language, category, environment, start year, team size, project duration and system size, as well as the following seven COCOMO* factors: required software reliability, execution time constraint, main storage constraint, virtual machine volatility, programming language experience, use of modern programming practices, and use of software tools. Simple empirical effort estimation models were then developed based on these productivity factors.

As organisational differences account for most of the productivity variation between projects in the ESA dataset, it was decided to develop general ESA effort estimation models with the data from one company removed, and then to test the general ESA models on the removed company. Simple company-specific effort estimation models based only on the factors found to affect the productivity of this particular company were also developed. The results of the best company-specific models were then compared with the models developed using the ESA dataset (Fig. 3).

Table 1. Variables in the ESA dataset

LANG		Application Programming Language
	ADA	Ada
	PAS	Pascal
	FOR	Fortran
	LTR	LTR
	C	C
	TAL	TAL
	COR	Coral
	AS	Assembler
ENV		Environment (Space, Military, Industry)
COMPANY		Company where project was developed
COUNTRY		Country where project was developed
CATEGORY		ESA Classification
	OB:	On Board
	MSG:	Message Switching
	RT:	Real Time
	GSE:	Ground Support Equipment
	SIM:	Simulators
	GRD:	Ground Control
	TL:	Tool
	OTH:	Other
TEAM		Maximum size of implementation team
DUR		Duration of project in months
KLOC		Kilo Lines of Code
YEAR		Start Year of Project
RELY		Required Software Reliability
TIME		Execution Time Constraint
STOR		Main Storage Constraint
VIRT		Virtual Machine Volatility
LEXP		Programming Language Experience
MODP		Use of Modern Programming Practices
TOOL		Use of Software Tools

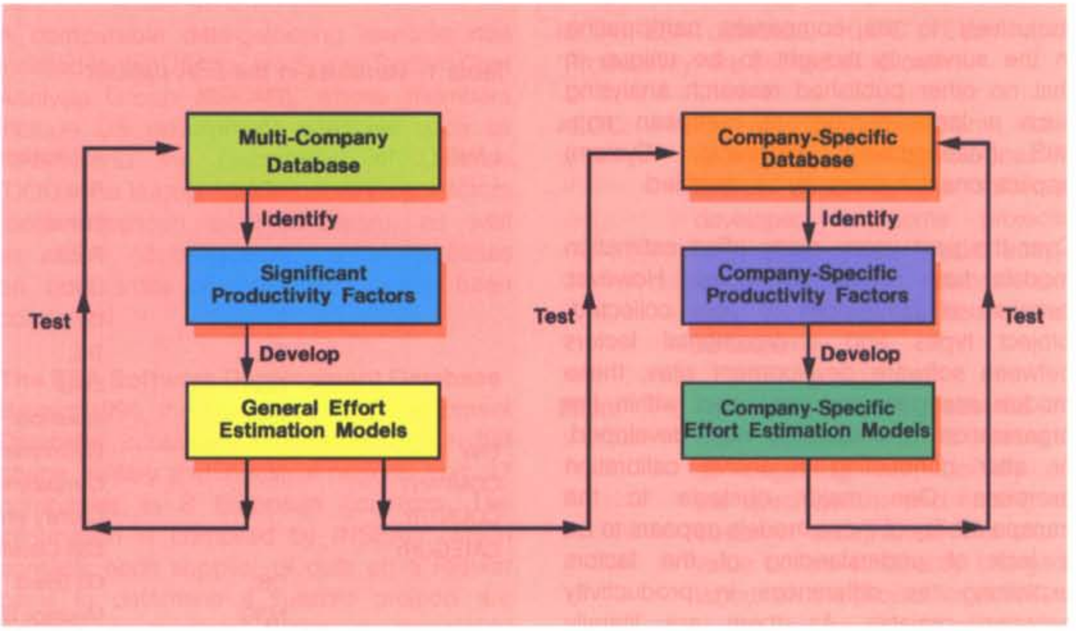
The research findings

As noted above, organisational differences were found to account for most of the productivity variations between projects in the dataset. This highlights the need for companies to establish their own software metrics databases, in addition to benchmarking their data against that of other companies. For benchmarking purposes, the best classification of the productivity of European space, military and industrial projects was determined to be by application, category and programming language.

It can also be concluded that accurate effort estimation is possible with just a very small number of productivity factors. Simple effort estimation models based on the size, in kilo-lines of delivered source code (KLOC), and the significant productivity factors of a given database are reasonably accurate when

* The Constructive COst Model is a major software engineering economics model developed by TRW in the United States.

Figure 3. Effort estimation model development and testing on databases



applied to projects from that database. However, effort predictions made on an individual company's software projects using a general model based on a multi-company database were shown to be less accurate than predictions made using a company-specific model. This underlines the importance of conducting further research into the appropriate set of productivity factors to be tracked in multi-company databases.

Management implications

The benefits of this research to ESA are strongly linked to the benefits obtained by the contributing companies. The Cost Engineering Section needs this software development database to fine-tune the parametric models in its cost-estimation tool and to support cost estimation by analogy when preparing cost estimates for new ESA projects. As basing new estimates on anything but comparatively recent developments is somewhat precarious, a continuous input of new projects is needed to keep the database up-to-date.

Clearly, companies are more likely to supply this data if there is an advantage to be gained by doing so. This research has shown that organisations can indeed benefit from contributing to multi-company software development databases, especially those that cover their particular application areas, through an increased understanding of the factors that influence the productivity of similar projects across companies and through the opportunity to benchmark their software development productivity. The analysis of this confidential data by an independant third party can lead to a greater knowledge for ESA and all contributing companies than would otherwise be the case.

Future developments

As previously indicated, it is desirable to maintain the present activity so as to have a better understanding of the process and to keep up to date in a rapidly changing domain. The participation of additional companies is sought in order to provide a wider basis for the analysis. Within ESA itself, with so many groups directly or indirectly involved in software-related activities, it is also most important to communicate and exchange ideas and information so as to optimise effort in this area.

A further aspect to be developed is the life-cycle approach, with software-maintenance costs being a very significant part of the overall cost of software development and application. Contacts with professional bodies such as the SSCAG and the ISPA (the US-based International Society of Parametric Analysts, which has many European members from the space sector) are important as a source of ideas and for the exchanging of both information and experience, because with limited resources available for such initiatives it is important to focus on the novel aspects and certainly to avoid 're-inventing the wheel'.

RENDEZVOUS WITH THE NEW MILLENNIUM

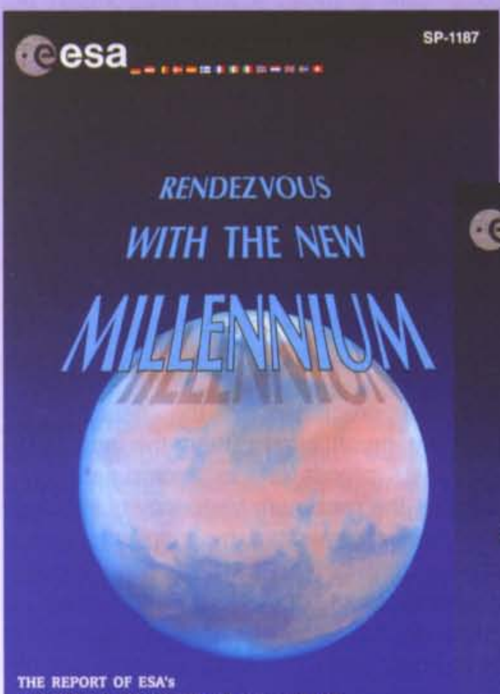
The Report of ESA's Long-Term Space Policy Committee

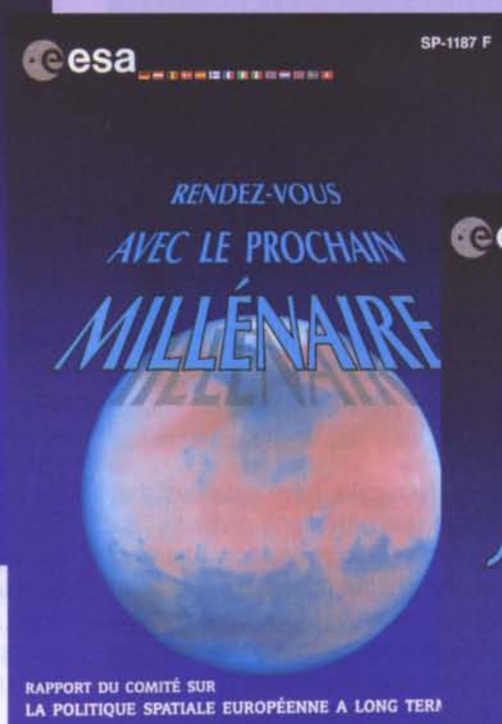
With 30 years of space activities behind us, we can now look forward to the next millennium on far more solid ground than the early pioneers ... At present, most space activities go from study phase to launch in about 10 years. The near-future is therefore already accounted for, and the major options for the next 20 years are also known. But what about the decades beyond that, and how will the world change over the next 50 years?

To identify a strategic vision for European space activities in the next century — one that will respond both to the challenges and threats facing humanity in the future — the ESA Council created a Long-Term Space Policy Committee (LSPC) in June 1993. The Commitee's task was to prepare a report on European space policy after the year 2000.

The LSPC chose to take a 50-year perspective in order to go beyond the mere extrapolation of current trends while still keeping in mind the present technological and financial constraints. The Committee analysed in depth the themes that it deemed to be of importance and collected the thoughts of recognised experts in relevant domains.

Its work has culminated in this report, *Rendezvous with the New Millennium*, which was presented to the ESA Council Meeting at Ministerial Level in Toulouse in October. The Ministers welcomed and endorsed the report: they expressed their satisfaction with the perspectives taken and have invited the Committee to continue to reflect on the long-term space policy for Europe.





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Document Classification and Searching – A Neural Network Approach

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Central Research Laboratories, Hayes, United Kingdom

This article introduces the basic concepts of Artificial Neural Networks and the related work that is currently being carried out at ESRIN in the field of document classification and searching. Some of the authors' ideas on the future directions that these techniques might take are also presented.

Introduction

The completeness and timeliness of information are vital elements for modern organisations, whether they be large intergovernmental agencies or small enterprises. The amount of information now available to them has become huge, and the growth trend is nearly exponential. This information-rich situation is actually a drawback since traditional search systems are starting to reach their limits. The use of these older systems is getting more and more difficult for the users who want to retrieve relevant information, as well as for the maintainers who have to carry out such activities as indexing, document classification and thesaurus maintenance. Two key requirements for solving this problem are:

- simplification of the search activities carried out by non-expert users, and
- reduction of maintenance costs.

Artificial Neural Networks have qualities that can be exploited successfully in order to fulfil these requirements. Documentation handling tasks are usually characterised by a lack of pre-defined rules; moreover, they can often be reduced to classification tasks. Research in the last 10 years has shown that Artificial Neural Networks are particularly good at dealing with such ill-structured classification tasks.

What is a neural network?

Nowadays, computers have astonishing processing powers and yet people are still much better at performing complex but everyday tasks like recognising an image or grasping an object. The reason for this superiority probably lies in the architecture of the human brain.

Study of artificial analogues of the structure of the human brain was pioneered by McCulloch and Pitts, who in 1943 proposed a model for its basic component, the 'neuron' (Fig. 1). The neuron can be represented as a cell body, the soma, with a single output fibre called the 'axon'. The axon propagates electrical pulses to other neurons or other structures such as muscles. The neuron receives its input from about 10^4 other neurons. The junctions, where input is received, are called 'synapses'.

The average human brain is likely to contain more than 10^{11} neurons. It is their interaction that produces the well-known, if often incomprehensible, phenomenon of 'human behaviour'.

Biological processes in the neurons are generally much slower than the analogous electronic processes in computers. For example, the maximum frequency of impulses that can be generated by a spiking neuron is less than 1000 per second. Modern microprocessors operate at frequencies of hundreds of millions of cycles per second. In the human brain, however, a huge number of strongly interconnected neurons work in parallel without centralised control. That enables the high-speed solution of certain tasks, as well as providing beneficial characteristics like fault-tolerance and the ability to learn and to generalise.

McCulloch and Pitts' studies suggested the possibility that devices can be constructed to imitate the operations of the human brain in certain respects. Such systems are generally termed 'Artificial Neural Networks'. In the sixties, B. Widrow proposed the model of an artificial neuron known as 'ADALINE', which

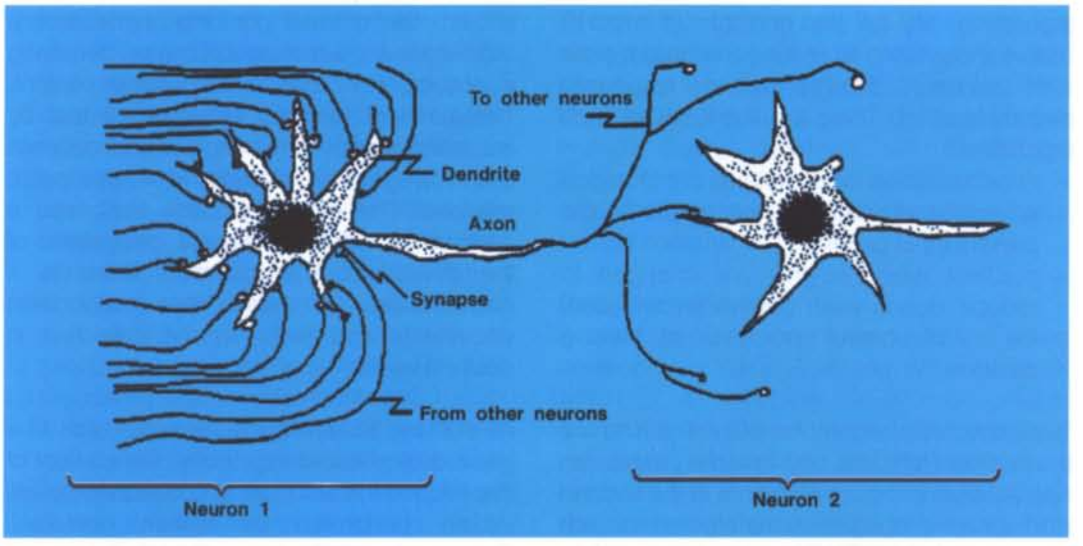

Figure 1. Neurons

constitutes the building block of nearly all artificial neural networks. ADALINE is an adaptive linear combiner cascaded with a threshold component (Fig. 2).

At time k, the output Y_k is a function $f(S_k)$ of the linear combination of the n input components X_{ik}. The output is

$$Y_k = f(W_{ik}X_{ik} - W_{0k}X_{0k})$$

where the function $f(\,)$ can be of different kinds, e.g. a linear, step, ramp or sigmoid function. The factors W_{ik} are called 'weights'. During the training process, these weights are modified by a learning algorithm.

According to I. Aleksander, Artificial Neural Networks are: *'networks of adaptable nodes which, through a process of learning from task examples, store experiential knowledge and make it available for use'.* It has been proven that a network with at least two layers of interconnected neurons can reproduce any function, provided that the number of neurons and weights is large enough. In other words, the input/output behaviour of any system, including computers and probably the human brain, can be reproduced by such networks. If we leave the problem of simulating human beings to speculative philosophers for the moment, it is certainly true that whatever can be done by a computer can also be done by an Artificial Neural Network, and vice versa. As matter of fact, Artificial Neural Networks can be implemented using traditional Von Neumann computers.

The reason for the explosion in interest in the scientific community in Artificial Neural Networks can be found in the advantages offered by their different architecture. Traditional computers are instructed via programs. Even the Artificial Intelligence systems are based on programs. Basically, these programs encode rules or 'relationships' between symbols representing real-world objects. In Artificial Neural Networks, the knowledge is not encoded by a programmer into a program, but is embedded in the weights of the neurons. Whilst Expert Systems and Knowledge-Based Systems try to emulate human conceptual mechanisms at a high level, Artificial Neural Networks try to simulate these mechanisms at a lower level. They

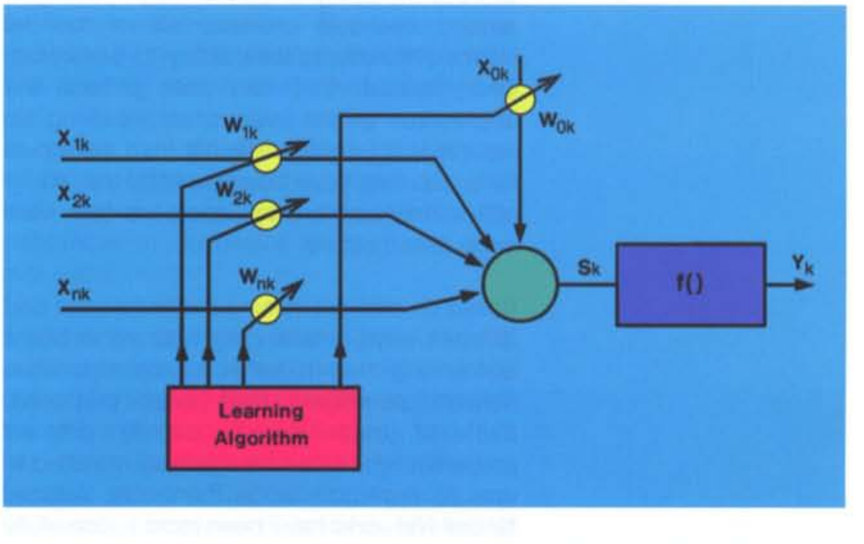

Figure 2. ADALINE

attempt to reproduce not only the input/output behaviour of the human brain, but also its internal structure. Knowledge is then stored in a non-symbolic fine-grained way. The weights can be set through a learning process, the goal of which is to obtain values which give the network the desired input/output behaviour.

Learning can be either 'supervised' or 'unsupervised'. Supervised learning is a process that incorporates an external teacher. The network is given a set of training patterns and the outputs are compared with desired values. The weights are modified in order to minimise the output error. Supervised algorithms rely on the principle of minimal disturbance, trying to reduce the output error with minimal disturbance to responses already learned. There are two kinds of such algorithms:

- *error correction rules:* weights are changed to reduce the error in the output to the present input pattern
- *gradient rules:* weights are changed to reduce, during each pattern presentation, the mean square error over all training patterns.

Two examples of algorithms of the first kind are the Widrow-Hoff delta rule, and the perceptron rule. An example of an algorithm of the second kind is back-propagation, the algorithm which almost single-handedly revived research into neural networks.

Unsupervised learning is a process that incorporates no external teacher; it is used, for instance, for building Self-Organising Maps, i.e. networks which take sets of input objects, represented by N-dimensional vectors, and map them into a topological space of some chosen dimensionality (often two-dimensional).

Besides the ability to learn through training, a second desirable characteristic of Artificial Neural Networks is their ability to generalise. Once trained, they can often provide the appropriate output even when receiving an input that is (slightly) different from the inputs for which they have been explicitly trained. In effect, they can answer questions that were never asked before.

Based on different training methodologies and different ways of arranging neurons in layers and linking them together, several alternative network paradigms have been proposed. Each of them exhibits slightly different properties which can be optimally matched to specific applications. On the whole, Artificial Neural Networks have been most successfully applied to problems in pattern recognition, adaptive control and business analysis. In general, they perform very successfully when dealing with ill-structured classification tasks.

ESRIN's activities

The tasks involved in handling and using document collections, namely, indexing, classification, thesaurus construction and search, are characterised by a lack of well-defined rules and algorithms to be used for their general solution. In general, they can be regarded as input/output classification tasks. Document classification, for instance, is based on the idea that similar documents should be relevant for the same query. Indexing is the act of describing or identifying a document in terms of its subject content. Thesauri and semantic networks are built by clustering similar terms into common classes and linking these classes with appropriate relations. The search process itself links a user query with the relevant documents of the collection. The common factor is a classification process that associates documents and terms of the collection in different ways.

All of these tasks require the exploitation of a good deal of knowledge about the content of the information and, as a consequence, are usually performed by human operators. Several attempts have been made to execute them in an automatic or semi-automatic way by adopting Artificial Intelligence techniques and, in particular, Expert and Knowledge-Based Systems. However, the need to encode explicitly the knowledge such systems require is often a stumbling block for their full exploitation. Artificial Neural Network techniques are a viable alternative, since the information they encode is learned from the raw data or a specification of the desired transformations.

ESRIN is currently carrying out a research activity with the objectives of:

- verifying the possibility of exploiting Artificial Neural Networks to improve the traditional documentation management and information retrieval systems
- producing a prototype which helps non-expert users search and browse through relevant information within large collections of documents and large collections of bibliographic references
- producing a prototype which helps the maintainers of the system perform document classification
- evaluating the prototype by measuring the effects of its integration into the existing systems in terms of performance and usability
- proposing detailed strategies for the implementation of operational neural-network systems to be integrated within the existing systems.

The reasons for this choice of technical orientation are as follows:

- Neural networks appear well-suited to pattern-recognition roles where the matching required is inexact; these flexible matching properties are expected to improve retrieval, particularly for inexperienced end users.
- Neural-network learning algorithms allow

matching and recognition software to be crafted using the structure of the data itself. The project has adopted an approach whereby the only training data required to construct a version of the system for a document collection is the document collection itself. This will allow the cataloguing of new document collections without time-consuming and costly manual work, and it will prevent the serious issues that would arise from attempting to handcraft sets of queries and their associated relevant document sets.

- While the training phase of neural-network development can be computationally intensive and require considerable periods of time to complete, once trained neural-network algorithms, if suitably organised, can prove both fast and efficient. Training for a collection can be performed off-line, and the trained networks can then offer a good user response time.

Basically, the prototype will provide two functions. Firstly, it will assist inexperienced users in accessing information through queries, dealing particularly with the need to allow users to go beyond the literal terms that are in their original query. This it will do by analysing the document collection and using the pattern of word occurrence to generalise the initial user query via an implicit thesaurus coded within the neural network. The system can suggest new terms related to those in the initial query, or carry out directly a search trying to match the semantic patterns of the query and of the documents.

Secondly, the system is meant to classify the documents into subject-related groups. These groups can be used for browsing when the user does not immediately start out with a well-defined information need, or does not know the exact content of the document collection. The cluster labels can also be incorporated into queries to broaden or narrow a search. From the several Artificial Neural Network paradigms that have been proposed in the literature, the following have been chosen and evaluated during the programme:

- Principal Component Analysis using Unsupervised Hebbian Learning (Oja Network).
- Principal Component Analysis using Multi-Layer Perceptrons.
- Selection and Prediction of High-Information Content 'Keywords' using Multi-Layer Perceptrons.
- Clustering using a Self-Organising Map (Kohonen Network).

Of these four options, only the first and the last proved to offer useful functionality. In the final prototype, an Oja Network is exploited to produce the thesaurus used for the explicit or implicit query expansion. A hierarchical implementation of the Kohonen Network is used for producing the clusters of subject-related documents.

Preliminary results

A preliminary version of the system is being developed for the ESA Microgravity Database, which is a collection of 975 documents and some associated images. The collection has been reformulated for this application, removing the image files from the catalogue and converting the collection to run under the UNIX version of the Ful/Text search engine produced by Fulcrum Inc.

First of all, a special dictionary of 2962 terms has been developed for the microgravity collection, some examples being:

- fabric (fabrication fabricated fabricate fabric)
- face (facing faces face)
- facet (facets faceted facet).

Each document has then been coded using the occurrence count of the word stems (included in the dictionary) in that document. The resulting vectors have been transformed using a vector pre-processing operation. A variety of pre-processing procedures, which alter the weighting associated with each word stem and compensate for differences in document length, have been evaluated.

A training set has been generated of pre-processed word stem vectors (in the case of the Microgravity Database this included all the documents in the collection) and this has been used to train the unsupervised Hebbian network. The resulting network acts as a data compression process, squeezing the 2962 word stem element vector into a 100-element semantic pattern vector. This process compensates for 'noise' in the documents (the spurious use of words unrelated to document subject), and generalises a query beyond the small set of words that it might contain.

Figure 3 shows the document density of the microgravity collection for two of the semantic patterns extracted by the Hebbian network. The large peak is an unfortunate artifact of the collection (all the documents here have an identical 'dummy' body, indicating that the results of the experiment are not yet available;

Figure 3. Density distribution of documents from the Microgravity Database, plotted according to two of the extracted semantic patterns

these documents appear very similar to the system, differing only in the wording of their titles).

The Hebbian network is used in several ways:
- to generate dynamically 'related terms' that may help the user to 'reconstruct' the initial query
- to achieve an implicit query expansion by directly matching the semantic patterns of the query to the semantic patterns of the documents
- as the document representation used by the Self-Organising Map.

Explicit query expansion
The user enters either single words, or a collection of words, and is provided with a set of other words which are associated with that word or query. Some examples from the microgravity collection are:

Blood:
1. 'lymphocyte' or 'lymphocytes'
2. 'culture' or 'cultured' or 'cultures' or 'culturing'
3. 'column' or 'columns'
4. 'blood'
5. 'activate' or 'activated' or 'activating' or 'activation' or 'activator' or 'activators' or 'active' or 'activities' or 'activity'
6. 'human'
7. 'cell' or 'cell's' or 'cells'
8. 'incubated' or 'incubating' or 'incubation' or 'incubator' or 'incubators'
9. 'proliferate' or 'proliferation'
10. 'glucose'

Electrophoresis:
1. 'electrophoresis'
2. 'separate' or 'separated' or 'separately' or 'separates' or 'separating' or 'separation' or 'separations' or 'separator' or 'separators'
3. 'cfe' or 'cfes'
4. 'buffer' or 'buffered' or 'buffers'
5. 'electrophoretic' or 'electrophoretically'
6. 'column' or 'columns'
7. 'dna' or 'dnas'
8. 'electric' or 'electrical' or 'electrically'
9. 'charge' or 'charged' or 'charges'.

Implicit query expansion
All of the documents in a collection are coded as their semantic patterns. A user can enter a query and the query can be directly matched against the semantic patterns of the documents. In this way, the user is supplied not only with those documents in which words from their queries occur, but also with *documents which are similar to these*. The following is an example query that hopefully makes this clear:

The original query is the single word 'art', and the six best-matched documents are:
1. Art in Space: Sampling and Artistic Preservation of the Space Vacuum
2. Art in Space: Coating of Glass Spheres by Vacuum Deposition Techniques
3. Reaction of Oil Paints on Canvas to Space Travel
4. Primary Mirror Production Using Vapour Deposition on a Quartz Plate
5. Adhesion of Metals
6 Oscillation of Semi-Free Liquid Spheres in Space.

The first three are clearly related and all contain the word 'art' within their title, abstract or body. The next three documents do not contain the word 'art', but represent documents in which techniques similar to those used in the first two (sculpture using glass spheres) are described.

Self-Organising Map
The other part of the system is a network which clusters documents into a hierarchy of subject-related categories. A Kohonen's self-organising topological map receives the documents as input (represented by the semantic vectors produced by the Hebbian network) and initially produces a small number of clusters (about 16); each cluster is then sub-clustered if it exceeds a user-specified size. Each cluster is also described by labels that can be included in standard Boolean queries. The relationships between the top-level clusters for the Microgravity Database are illustrated in Figure 4.

The clusters are:

1 Documents: 56
Texus Setup Rocket Series Spacelab
2 Documents: 47
Crystal Transport Growth Protein Vapour
3 Documents: 61
St Canister Solder Special Away
4 Documents: 30
Electrophoresis Separate Cfe Column Field
5 Documents: 31
Diffusion Coefficient Sn Interdiffusion Self
6 Documents: 46
Culture Cell Centrifugal Lymphocyte G
7 Documents: 67
Microstriation Zone Crystal Growth Doped
8 Documents: 29
Synthesized Soon Yet Concern Ha
9 Documents: 153
Particle Solidified Alloy Al Melt
10 Documents: 104
Critical Phase Marangoni Droplet Temp.
11 Documents: 75
Drop Rotate Oscillate Bridge Film
12 Documents: 215
Synthesized Soon Yet Concern Ha
13 Documents: 20
Foam Metal Ga Bubble Reaction
14 Documents: 8
Protoplasm Fusion Electrofusion Cell Plant
15 Documents: 16
Consort Payload Recover Rocket Starfire
16 Documents: 17
Well Block Consort Type Mda

The clusters (8 & 12) with word descriptions 'Synthesized Soon Yet Concern Ha' represent all the documents with the identical dummy body (these words all occur in that body). Subclusters of these clusters do divide the documents using the differences in their titles.

Some example documents from a cluster, showing how well they represent divisions based on subject, are given in the following list – the documents are from cluster 6 'Culture Cell Centrifugal Lymphocyte G' and clearly represent biological experiments conducted in zero gravity:

1. The Effect of Microgravity on Mammalian Cell Polarization at the Ultrastructural Level
2. The Paramecium Experiment. Demonstration of a Role of Microgravity on Cells
3. Effects of Microgravity on Lymphocyte Activation (In-vitro)
4. Attachment of Human Embryonic Kidney (HEK) Cells to Microcarrier Beads in Microgravity
5. Antibacterial Activity of Antibiotics in Space Conditions

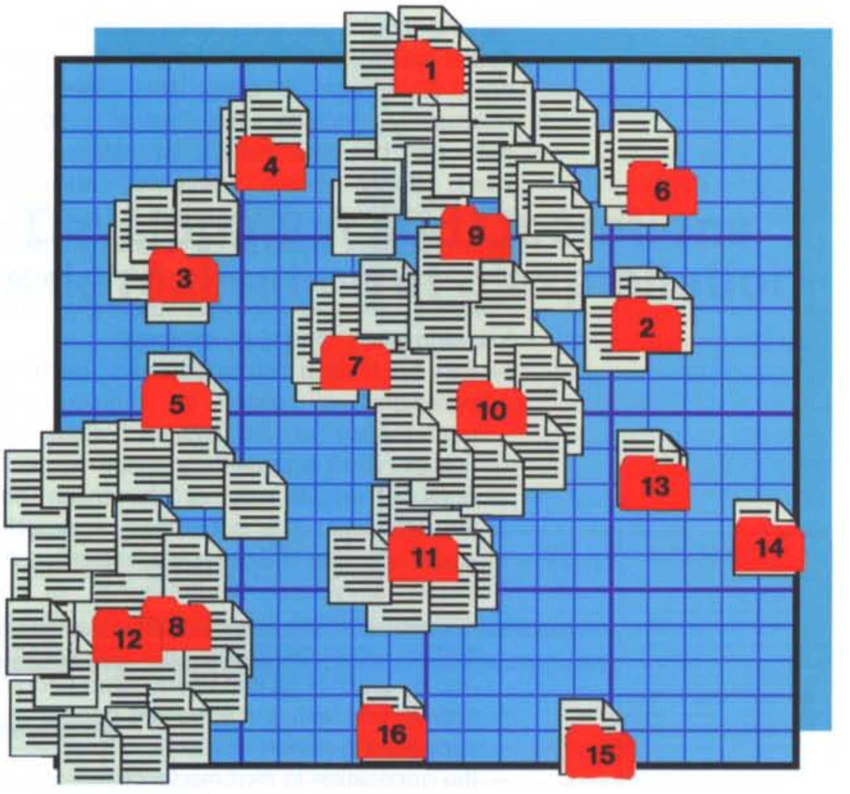

Figure 4. Relative semantic distances of top-level clusters in the Microgravity Database

6. Differentiation and Embryogenesis in Aniseed Cell Cultures in Microgravity
7. Effects of Microgravity on Lymphocyte Activation (Ex-vivo)
8. Friend Leukemia Virus Transformed Cells Exposed to Microgravity in the Presence of Dimethylsulfoxide
9. Proliferation and Performance of Hybridoma Cells in Microgravity
10. Dynamic Cell Culture System

Other clusters similarly represent fairly clear subject divisions. However, not all the divisions represent a subject selection which one might automatically make; for example, three papers are listed together because they all use hypodermic syringes as part of the experimental procedure.

If users have a pre-defined subject division and wish their collection to match this, then a supervised neural-network approach will match their expectations better. The advantage that the whole unsupervised approach adopted in this work has, though, is that the entire process of constructing the system can be performed with minimal user intervention beyond setting up the initial options.

The future

Based on the encouraging preliminary results of the project, the authors believe that it will be relatively easy to incorporate the systems described here into a number of operational applications at ESRIN. For instance, the electronic version of the paper that you are just reading could be soon searchable with a neural system, and it could be possible to get hold of it with a query that does not necessarily include the words 'neural networks', but does include, for instance, the words 'fuzzy search'. Moreover, research should continue in directions that are bound to return excellent results by complementing and improving the existing tools for document classification and search. Basically, the following areas need to be explored:

- the application of supervised learning paradigms in order to improve the performance of the system: whilst an unsupervised approach is easier, since it does not require external intervention, on the other hand a supervised approach could provide much better results in situations where a thesaurus or a knowledge base already exists or when a human expert can interact with the system; real life teaches us that uneducated people survive very well, but educated people are supposed to perform better
- the application to multimedia collections in order to search and retrieve not only text but also images and movies: images can be analysed and classified by neural networks better than a text document because the semantic component is less relevant
- the automatic definition of hypermedia links in order to improve the browsing functionality.

Finally, we would like to stress the importance of Artificial Neural Networks in the Internet environment. There we find, on a worldwide scale, the same problems that single organisations face because of the huge amount of potentially available documentation and the difficulty in searching and retrieving the relevant portion for a specific task. Two applications will have to be considered in the near future:

- the integration of Artificial Neural Networks into the existing WWW search engines like Lycos, Yahoo and Alta Vista, which currently offer keyword searching only
- the integration of the Artificial Neural Networks with the technology of the Intelligent Software Agents: these software systems are able to travel on the network in order to explore, on behalf of the user, heterogeneous and geographically distributed systems; currently, the development efforts are focused on the interaction with the network, but the introduction of neural techniques will add the 'intelligence' needed in order to fulfil the user requirements better.

Programmes under Development and Operations
Programmes en cours de réalisation et d'exploitation

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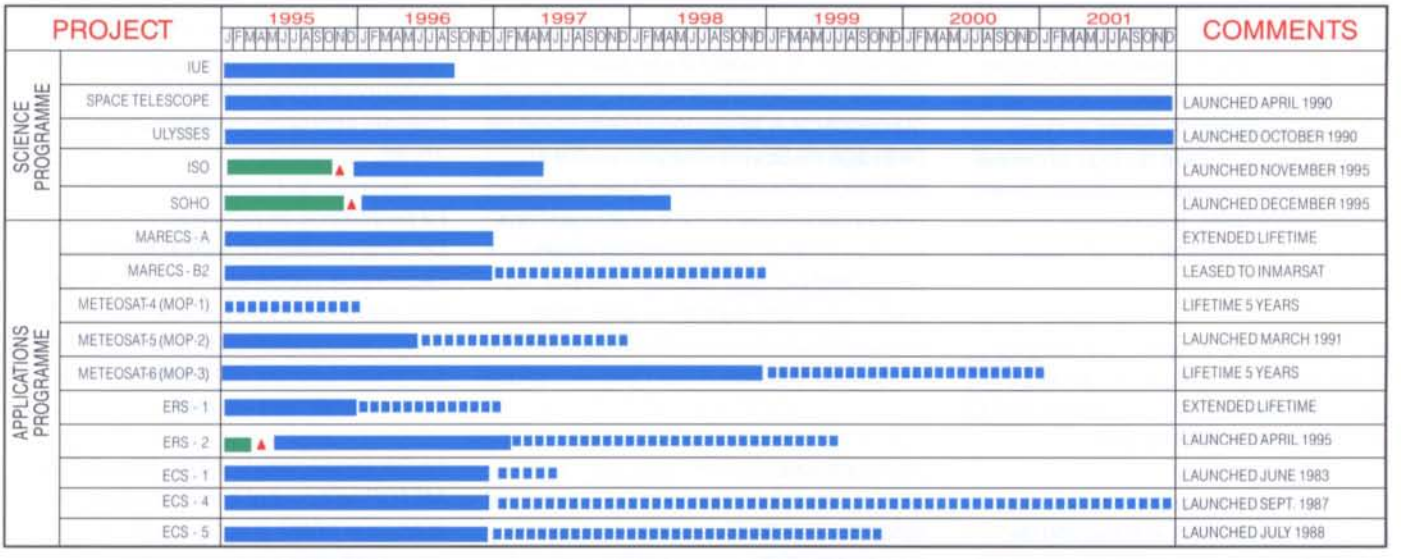

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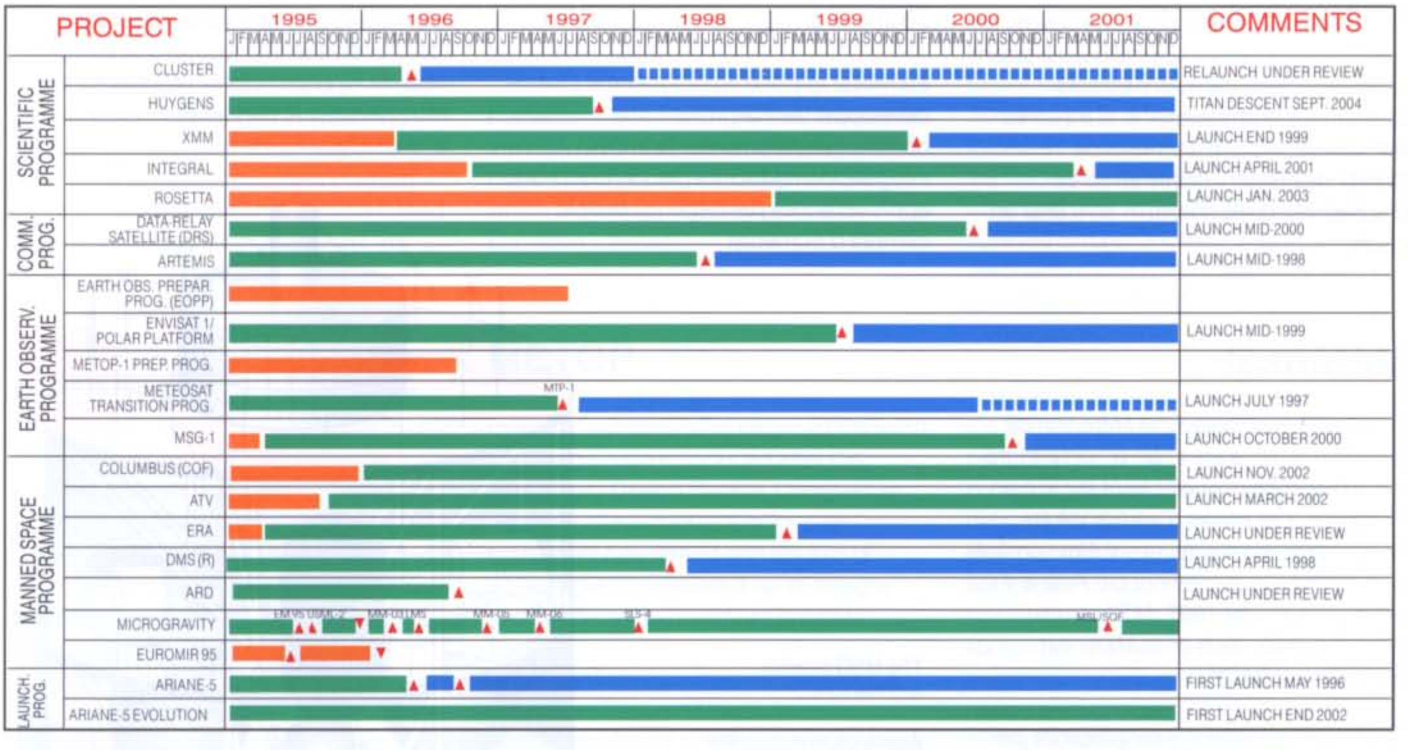


■ DEFINITION PHASE
■ OPERATIONS
■ MAIN DEVELOPMENT PHASE
■■■ ADDITIONAL LIFE POSSIBLE
▲ LAUNCH/READY FOR LAUNCH
▼ RETRIEVAL

SOHO

Les activités de recette du véhicule spatial se sont achevées fin mars et l'équipe ESA/Matra Marconi Space chargée de cette phase a rédigé un rapport détaillé.

L'événement marquant de la phase de recette a été la résolution d'un problème affectant l'instrument VIRGO, dont l'un des couvercles se refermait systématiquement après ouverture. Des simulations analytiques et des essais conduits en parallèle au sol sur les rechanges de vol de cette expérience ont révélé une sensibilité à certains paramètres non décelée jusque là. Le chercheur principal responsable de l'expérience et les équipes de l'ESA et de l'industrie ont uni leurs efforts pour mettre au point une solution reposant sur une modification temporaire du logiciel central de bord. Cette procédure ayant donné les résultats escomptés, le couvercle récalcitrant a finalement pu être ouvert le 27 mars.

Le 16 avril, SOHO a été remis à l'équipe scientifique dirigée par l'ESA, qui se trouve pour l'essentiel au Centre Goddard (GSFC) de la NASA, dans le Maryland.

Une conférence de presse a eu lieu au siège parisien de l'ESA le 2 mai afin de présenter les premiers résultats de SOHO, qui sont excellents, et de faire connaître la contribution qu'apportera cette mission dans le domaine de la physique solaire. Le flux des observations scientifiques a atteint en mai le niveau prévu et plusieurs campagnes d'observations, auxquelles participent divers instruments de SOHO, des observatoires au sol et d'autres véhicules spatiaux, sont déjà en cours.

Météosat

Le satellite du programme Météosat de transition, MTP, a été entièrement intégré sur le plan mécanique et testé sur le plan électrique. Les essais d'ambiance au niveau de la recette devraient être conduits à l'automne. Le lancement par Ariane 4 est prévu début juillet 1997. MTP sera le dernier satellite de la série Météosat opérationnel (MOP).

Après son lancement, il sera exploité par Eumetsat et fournira régulièrement des images météorologiques de l'Europe, comme le fait actuellement Météosat-5, dont le satellite de réserve Météosat-6 se trouve déjà en orbite. Ces deux derniers satellites ont eux aussi été fabriqués dans le cadre de contrats attribués par l'ESA.

Météosat de deuxième génération

La phase principale de réalisation (phase C/D) s'est achevée comme prévu en avril avec la dernière revue préliminaire de conception (PDR) au niveau système. Le feu vert a été donné à l'industrie pour la fabrication du modèle d'identification et du modèle thermique/mécanique, sauf en ce qui concerne le télescope et l'ensemble de balayage de SEVIRI (imageur visible et infrarouge amélioré non dégyré), dont la conception doit être revue et adaptée aux environnements thermiques qui seront rencontrés pendant le lancement puis en orbite. Une PDR supplémentaire étant prévue en octobre, le calendrier de SEVIRI est devenu critique.

Les négociations avec l'industrie au sujet de l'approvisionnement des trois satellites MSG-1, -2 et -3 ont été menées à terme. Le lancement de MSG-1 est maintenant fixé en octobre 2000, celui de MSG-2 devrait avoir lieu en 2002 tandis que MSG-3 sera entreposé (pour servir de réserve) en 2003.

Eumetsat apporte au programme ESA de développement de MSG-1 une contribution forfaitaire et finance intégralement MSG-2 et MSG-3, qui sont approvisionnés par l'Agence pour le compte d'Eumetsat.

METOP

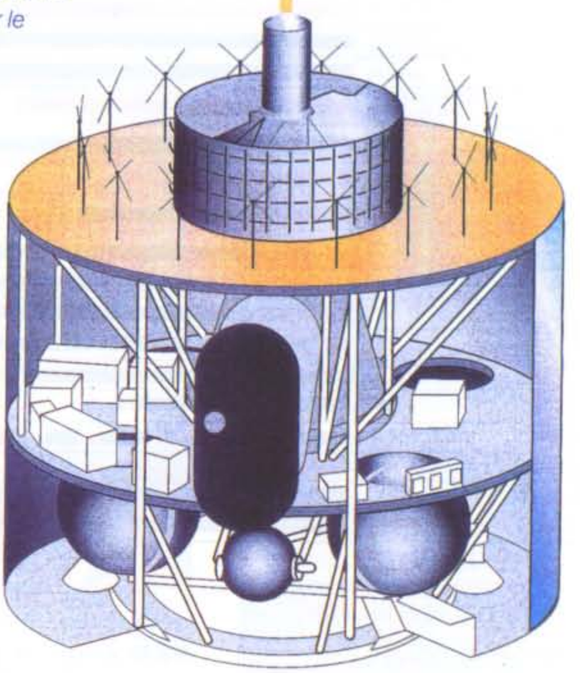
Les activités industrielles ont repris après un arrêt à l'issue de la revue préliminaire de conception. On procède actuellement au choix des sous-traitants qui seront chargés, à la suite d'appels d'offres ouverts, des nouveaux équipements, l'objectif étant de parvenir dans les plus brefs délais à un ensemble harmonisé de concepts et d'interfaces.

Les activités relatives au démonstrateur de l'ASCAT sont terminées; la conception de cet instrument est très avancée et la phase C/D peut démarrer.

L'élaboration des documents de vérification des interfaces des instruments a beaucoup progressé et un niveau de maturité approprié est généralement atteint.

La proposition de programme et la Déclaration relatives à METOP ainsi que l'Accord de coopération ESA/Eumetsat ont été examinés lors des réunions des participants potentiels et directement avec Eumetsat. Leur contenu a été considérablement amélioré.

La Déclaration relative à la phase C/D de METOP ne pouvant entrer en vigueur avant la fin de la phase B actuellement en cours dans l'industrie, une phase C0 a été proposée aux Etats participants. Elle prévoit la poursuite des activités industrielles relatives au lancement de l'approvisionnement des articles à long délai de livraison, jugées essentielles si l'on veut maintenir le calendrier envisagé pour la réalisation.



The MSG satellite architecture

Architecture du satellite MSG

SOHO

The spacecraft commissioning activities were concluded at the end of March and a comprehensive report has been compiled by the ESA/Matra Marconi Space team in charge of this phase.

A very important achievement during the commissioning phase was the solution of a problem with the VIRGO instrument, one of the covers of which had been repeatedly rebounding back to its closed position when commanded open. Analytical simulations and parallel tests on the ground with the experiment flight-spare units confirmed a previously undetected sensitivity to particular parameters. A joint effort involving the experiment's Principal Investigator and the ESA and industrial teams produced a solution to the problem involving temporary modification of the central onboard software. The modified procedure worked as foreseen and the reluctant cover was finally opened on 27 March.

On 16 April, the SOHO mission was handed over to the ESA-led scientific team, most of whom are currently based at Goddard Space Flight Center (NASA/GSFC) in Maryland (USA).

A Press Conference was held at ESA Headquarters in Paris on 2 May to present the excellent first results from SOHO and to publicise the opportunities that this mission offers for the advancement of solar physics. During May, the flow of scientific observations has reached the planned level, with several joint observing operations already in progress in which various SOHO instruments, ground-based observatories and other spacecraft are cooperating.

Meteosat

The Meteosat Transition Programme (MTP) spacecraft has now been fully mechanically integrated and electrically tested. The acceptance-level environmental tests are scheduled to take place in the autumn. Launch, on an Ariane-4 vehicle, is planned for the beginning of July 1997. The MTP spacecraft will be the last of the Meteosat Operational programme (MOP) design to be launched.

Once launched, the spacecraft will be operated by Eumetsat to provide the regular weather pictures over Europe which are currently being provided by Meteosat-5, with Meteosat-6 as the in-orbit spare, these two spacecraft having also been built under ESA spacecraft supply contracts.

Meteosat Second Generation

The MSG main development phase (Phase-C/D) was concluded in April with the final system-level Preliminary Design Review (PDR), as planned. Engineering-model manufacture and thermal/mechanical-model manufacture have been released to industry, except for the telescope and scan assembly of SEVIRI (the Spin Enhanced Visible and Infra-Red Instrument) which, in order to be compatible with both the launch and the in-orbit thermal environments, needs redesign. A supplementary PDR is now planned for October, which puts the SEVIRI schedule on a critical path.

Negotiations with industry for the procurement of the three satellites MSG-1, 2 and 3 have been concluded. Launch of MSG-1 is now scheduled for October 2000, with MSG-2 to be launched in 2002 and MSG-3 to go into storage (as a backup) in 2003.

Eumetsat is contributing a fixed amount to the ESA MSG-1 development programme, but is fully financing MSG-2 and MSG-3, which are being procured by ESA on Eumetsat's behalf.

METOP

Industrial activities have resumed following a holding phase introduced after the Preliminary Design Review. Competitive selection of subcontractors for new equipment has started with the aim of achieving a consolidated set of designs and interfaces as quickly as possible.

The ASCAT demonstrator activities have been completed and the instrument'design is in an advanced stage and ready for the start of Phase-C/D.

The generation of Instrument Interface Control Documents has progressed considerably and has generally reached an appropriate degree of maturity.

The METOP Programme Proposal and Declaration and the ESA/Eumetsat Cooperation Agreement have been debated within the framework of Potential Participant Meetings, and also in direct discussions with Eumetsat. Considerable progress has been made in refining their content.

As the METOP Phase-C/D Programme Declaration cannot enter into force prior to the end of the present industrial Phase-B, a Phase-C0 has been proposed to the Participating States. This includes the continuation of industrial activities orientated towards the initiation of long-lead-item procurements, considered essential if the envisaged development schedule is to be maintained.

ERS

The ERS-1 payload was put into hibernation on 3 June. SAR imaging is still being conducted for an average of two passes per day over Kiruna (S) for interferometry purposes. The payload will be reactivated every second 35-day repeat cycle for 3 days to perform maintenance activities.

ERS-2 has completed its first year in orbit. Some minor anomalies have occurred on the Active Microwave Instrument (AMI) and the Radar Altimeter (RA), leading to data interrupts. The ATSR-2 instrument has suffered a major anomaly in its scanning mechanism which has interrupted its operations, and this problem is still under investigation.

The Global Ozone Monitoring Experiment (GOME) continues to demonstrate stable performance. A minor problem in the complex ground-processing system has delayed the distribution of data to the full user community, but this is expected to be completed by July this year. GOME's operation and data gathering has been somewhat affected by the continuing investigations into the ATSR-2 anomaly. It is hoped both to obviate this adverse impact on the GOME and to recover the operation of the infrared radiometer by means of a

ERS

La charge utile d'ERS-1 a été mise en hibernation le 3 juin. Des images du SAR sont toujours recueillies à raison d'une moyenne de deux passages par jour au-dessus de Kiruna (S), à des fins d'interférométrie. La charge utile sera remise en fonctionnement pendant trois jours tous les deux cycles de 35 jours, pour des activités de maintenance.

ERS-2 a achevé sa première année en orbite. Des anomalies mineures ont affecté le détecteur actif à hyperfréquence (AMI) et l'altimètre radar (RA), ce qui a provoqué des interruptions dans la transmission des données. Une anomalie majeure s'est produite dans le mécanisme de balayage de l'ATSR-2, qui a dû être arrêté. Ce problème est à l'étude.

Le fonctionnement de l'expérience de surveillance de l'ozone à l'échelle du globe (GOME) reste stable. Un problème mineur dans le système de traitement au sol, de grande complexité, a retardé la diffusion des données aux utilisateurs, qui devraient toutefois tous avoir été servis d'ici juillet 1996. L'exploitation de GOME et la collecte de données ont été quelque peu perturbées par le déroulement de l'enquête sur l'anomalie de l'ATSR-2. On espère remédier à cet inconvénient et reprendre l'exploitation du radiomètre dans l'infrarouge en modifiant le logiciel. L'instrument PRARE continue à fonctionner normalement.

Le fonctionnement du satellite ERS-2 reste stable. Il a été proposé aux délégations de prolonger son exploitation jusqu'à la date fixée pour le lancement d'Envisat.

Huygens

Plusieurs étapes significatives ont été franchies depuis le dernier bulletin, ce qui reflète les progrès réguliers du projet Huygens et de la mission Cassini.

Toutes les mesures demandées à l'issue de la Revue critique de conception ont été examinées, même celles portant sur la revue externe indépendante d'aptitude au vol et sur la revue d'homologation du matériel (HRCR) auxquelles participe le JPL de la NASA, à l'occasion d'une réunion tenue en mars dont les conclusions ont été positives. Le feu vert a notamment été donné à l'issue de la HRCR pour l'envoi par mer aux Etats-Unis du modèle d'identification de la sonde, en vue de son intégration au véhicule spatial Cassini et des essais combinés.

Une revue de la mise en oeuvre du secteur sol (GSIR) a également eu lieu en mars à l'ESOC (D) et a montré que l'avancement des travaux tant du point de vue du matériel que du logiciel est parfaitement satisfaisant. Le modèle d'identification de la sonde a donc été envoyé au JPL en avril.

L'intégration et les essais d'interface avec Cassini se sont eux aussi parfaitement déroulés, de même que les séquences de vérification du fonctionnement de la sonde en orbite. Ces tâches, qui ont été menées par une équipe commune ESA/industrie, ont montré l'intégrité de la sonde; celle-ci a donc pu être laissée au JPL, avec une équipe industrielle de soutien très réduite, en vue des activités ultérieures qui seront menées sur l'ensemble sonde/orbiteur.

L'intégration et les essais du modèle de vol de la sonde ont progressé, bien que quelques expériences n'aient pas encore été livrées aux normes de vol. Le travail supplémentaire occasionné par la livraison tardive d'expériences, l'échange de modèles, etc., n'est pas sans incidence sur le calendrier, et il a fallu reporter la revue de recette pour le vol à février 1997. Ce report est sans risque pour la date de lancement.

A la fin mai, les préparatifs des principaux essais système, de l'essai thermique sous vide et de l'essai à basse température de rentrée dans l'atmosphère de Titan étaient bien avancés.

XMM

La revue préliminaire de conception (PDR) ayant été menée à bien en novembre dernier et le dossier de données préparé pour celle-ci servant également de proposition technique pour la phase principale de réalisation de XMM (phase C/D), la proposition financière a été soumise et évaluée. Ses résultats et les recommandations formulées ont été présentés au Comité de la politique industrielle (IPC) de l'Agence, qui a approuvé l'exécution du programme à sa réunion du 15 mars.

Le contrat de fabrication du satellite XMM, dont la livraison est fixée au 1er juin 1999, a été signé le 21 mars avec le maître d'oeuvre, Dornier Satellitensysteme GmbH. L'adoption d'un nouveau style de gestion avec une communication plus directe entre les différents niveaux a eu un effet positif sur le respect du calendrier.

La conception des instruments, trois caméras dans le rayonnement X, deux spectromètres à grille de réflection et un moniteur optique, est arrêtée et leur rendement devrait être excellent. Les essais des modèles électriques des instruments sont en cours. Il est prévu de mener à l'automne les essais dans le rayonnement X sur les modèles de qualification des miroirs.

La réalisation des miroirs travaillant dans le rayonnement X, sous la responsabilité directe de l'ESA, se déroule comme prévu. Les essais dans l'UV extrême et le rayonnement X, les essais en vibrations et les essais thermiques du modèle de qualification du module de miroirs complet, qui se compose de 58 miroirs emboîtés, ont été menés à bien. La fabrication du premier modèle de vol de l'araignée de montage des miroirs est terminée et celle des trois autres est bien avancée. Environ un quart des 232 miroirs aux normes de vol ont été fabriqués et les études métrologiques montrent qu'ils sont de bonne qualité.

Le module de servitudes de XMM présente une communauté de conception avec Intégral. Les éléments à long délai de livraison ont été commandés en 1995 et les PDR des équipements du satellite sont en cours. La production des modèles électriques, qui doivent être livrés à la fin de l'année, est en cours et la fabrication des modèles de structure a débuté.

Intégral

Le maître d'oeuvre du satellite, Alenia Spazio (I), a poursuivi ses travaux de définition, qui doivent tenir compte de la communité avec le module de servitudes de XMM. Parallèlement, il a évalué avec l'Agence les propositions reçues en réponse aux appels d'offres ouverts relatifs aux équipements propres à Intégral. Les résultats de ces activités figureront dans le dossier de données de la revue software change. The PRARE instrument continues to operate nominally.

All ERS-2 spacecraft performances remain stable. An extension of ERS-2 operations until the expected Envisat launch date has been proposed to the ESA Delegations.

Huygens

The period under review has seen a number of significant achievements that reflect the continuing successful progress of the overall Huygens project and Cassini mission.

The Critical Design Review action-item close-out meeting reviewing all actions including those relating to the External Independent Readiness Review and the Hardware Readiness Certification Review (HRCR), both with the participation of NASA/JPL, were successfully carried out during March. The HRCR in particular led to the approval to ship the engineering-model Probe to the USA for subsequent integration and combined testing with the Cassini spacecraft.

Also during March, a Ground Segment Implementation Review (GSIR) was held at ESOC (D), which showed that the state of implementation readiness for both hardware and software was fully satisfactory. The engineering-model Probe was subsequently shipped to JPL during April.

Integration and interface testing with Cassini was also completely satisfactory, as too was the running of the Probe in-orbit checkout sequences. These tasks, accomplished by a combined ESA/industry team, proved the integrity of the Probe, allowing it to be left at JPL, with just a very small supporting industrial team, for future combined Orbiter/Probe activities.

Flight-model Probe integration and testing has progressed successfully, even though some experiment units are currently 'non-flight'. The extra work brought about by late experiment deliveries/model exchanges, etc. has had an impact on the schedule, causing the Flight Acceptance Review to be shifted to February 1997. This does not endanger the launch date.

By the end of May, preparations were well in hand for the major system tests, the thermal-vacuum and Titan entry cold test.

XMM

Following the successful Preliminary Design Review (PDR) last November, the data package for which also constitutes the technical proposal for the XMM Main Development Phase (C/D), the financial proposal was submitted and evaluated. The results and recommendations were presented to the Agency's Industrial Policy Committee (IPC), which approved the programme's implementation at its meeting on 15 March.

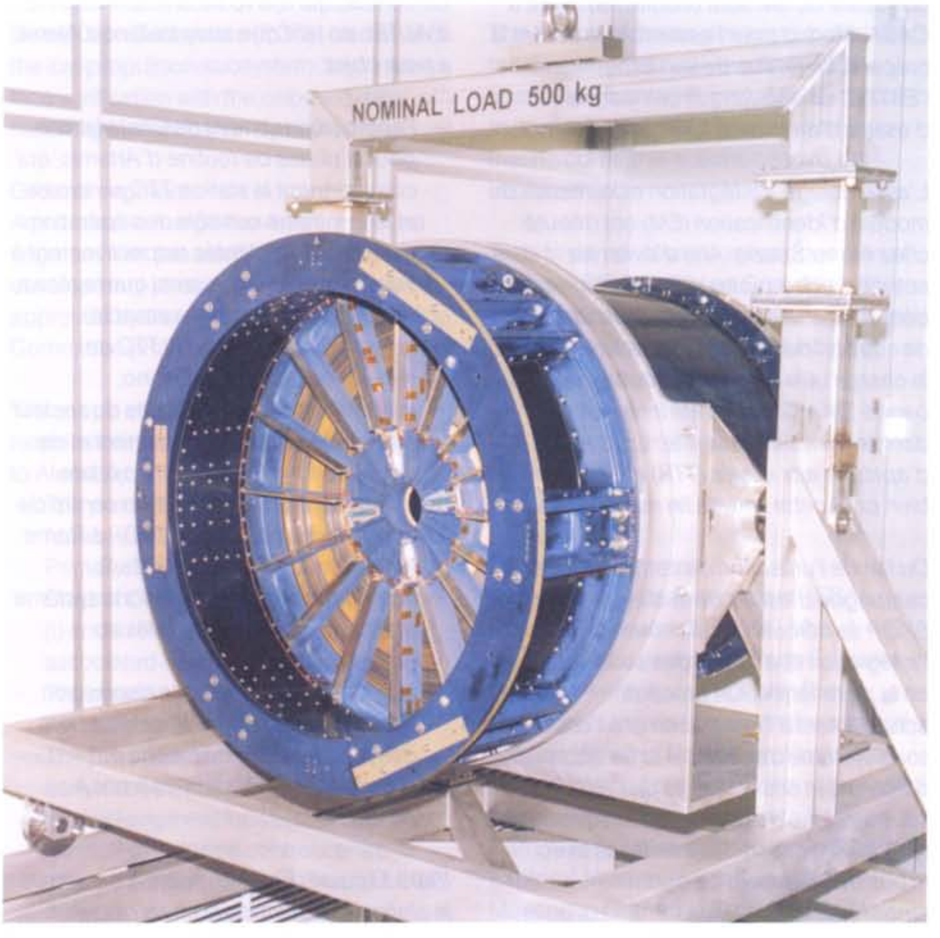
The contract to build the XMM spacecraft, due for delivery on 1 June 1999, was signed with Dornier Satellitensysteme GmbH, the prime contractor, on 21 March.

The adoption of a new management style with more direct communication between the various levels has had a positive effect in holding the schedule.

The design of the experiments, three X-ray cameras, two reflection grating spectrometers and an optical monitor, is complete, with very good performance predictions. Testing of electrical models of the instruments is in progress. X-ray testing with the qualification-model mirrors is foreseen for the autumn.

The development of the X-ray mirrors, under ESA's direct responsibility, is proceeding as planned. The qualification model of the complete mirror module, consisting of 58 nested mirrors, has successfully completed EUV and X-ray testing, as well as vibration and thermal tests. The first flight-model spider has been manufactured, and the next three are well advanced. Approximately a quarter of the 232 flight mirrors have been produced and the metrology indicates that they are of good quality.

The XMM service module is designed for commonality with Integral. Long-lead items have been ordered in 1995, and the PDRs for the spacecraft units are now being

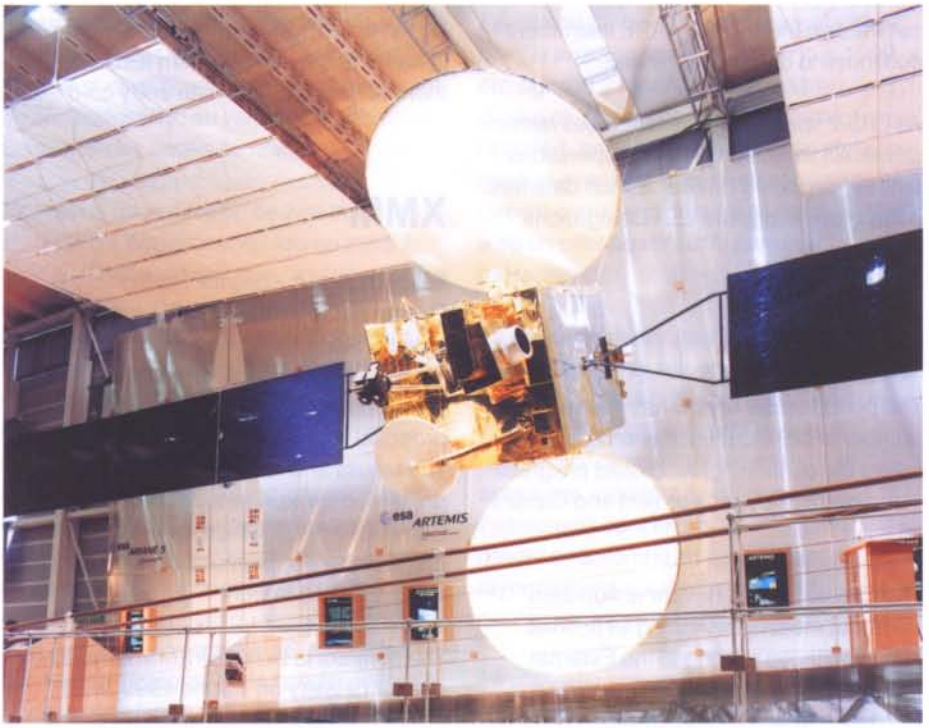


Modèle de qualification du module de miroirs de XMM

Qualification model of the XMM mirror module *préliminaire de conception et dans la proposition de phase C/D, qui doit être soumise début juin.*

La première revue de la charge utile a eu lieu et a permis de convenir de la définition des interfaces techniques entre les instruments et le satellite.

Pour ce qui est du secteur sol, une revue similaire a eu lieu au sujet du centre des données scientifiques qui traitera les données des instruments d'Intégral. Les activités relatives au secteur sol se sont en outre concentrées sur la définition des plans de mise en oeuvre, compte tenu des besoins des projets.



Model of the Artemis spacecraft

Le véhicule spatial Artemis

Artemis

Satellite

La structure principale du modèle structurel (SM) a été livrée à BPD, Colleferro (I), pour l'intégration du sous-système de propulsion et l'installation des instruments dans les éléments qui seront inaccessibles ultérieurement. Cette activité, à laquelle participe également CASA (E) et Alenia (I), devrait s'achever début juillet de cette année. La structure principale du SM sera ensuite renvoyée à CASA, Madrid pour l'assemblage final et la préparation en vue de son expédition à l'ESTEC, où débutera la campagne d'essais d'ambiance fin août.

L'assemblage, l'intégration et les essais du modèle d'identification (EM) ont débuté chez Alenia Spazio. Afin d'éviter les activités redondantes d'intégration et de démontage des panneaux de la structure de support de charge utile fictive sur l'EM, la charge utile de relais de données en bande S/Ka (SKDR) a été intégrée directement sur le satellite. La revue d'aptitude aux essais (TTR) a été menée à bien pour cette activité fin mai.

Du fait de l'utilisation de cette méthode, la campagne d'essais de la charge utile SKDR se déroule parallèlement à l'intégration et à l'essai des sous-systèmes de la plate-forme. On procède actuellement à l'intégration et à l'essai du sous-système de contrôle et de distribution d'énergie et des éléments du sous-système de propulsion ionique, ainsi qu'à la vérification des interfaces avec le bus de traitement de données embarqué.

Secteur sol

Une proposition visant à intégrer le secteur sol d'Artemis dans le contrat principal relatif à la phase de développement principal du satellite (phase C/D) a été approuvée par le Comité de la politique industrielle (IPC) de l'Agence les 8 et 9 mai.

Ce contrat, qui relève de la responsabilité d'ALTEL en tant que sous-traitant d'Alenia, a pour objet:

- *l'approvisionnement des installations pour la phase de routine d'Artemis, qui comprennent la station TTC principale et le Centre de contrôle des opérations devant être implantés respectivement à Fucino (I) et à Rome, ainsi que le réseau de télécommunications associé;*
- *la fourniture de la station TTC de réserve en bande S à Fucino;*
- *la fourniture des installations du secteur sol pour la phase de lancement et de début de fonctionnement en orbite (LEOP), qui comprennent un centre de contrôle des opérations LEOP à Rome et un réseau LEOP en bande S;*
- *la préparation des installations système et des opérations préalables au lancement;*
- *la commande du satellite depuis son injection sur orbite de transfert et lors des phase LEOP, de recette et d'exploitation pendant trois ans à poste.*

Indra Espacio (E) est le maître d'oeuvre de la station TTC principale en ce qui concerne sa conception, sa réalisation et les opérations d'assemblage, d'intégration et d'essai au niveau système, avec Rymsa (E) comme sous-traitant du sous-système d'antenne et Laben (I) pour le sous-système en bande de base. Les fournisseurs d'équipements comprennent ERA (GB) et MAC (I).

Nuova Telespazio est responsable de la conception et de la réalisation des centres de contrôle des opérations (OCC) ainsi que de la préparation et de l'exécution des opérations. Les sous-traitants comprennent Dataspazio (I), GMV (E) et ELCA (CH) pour le logiciel OCC.

Telespazio bénéficiera également d'un soutien technique direct et de services d'expertise-conseil de l'ESOC.

Terminal Silex LEO

L'intégration du modèle de vol du terminal Silex LEO progresse de manière satisfaisante. Les essais d'ambiance débuteront à la mi-juillet et s'achèveront avant la fin de l'année.

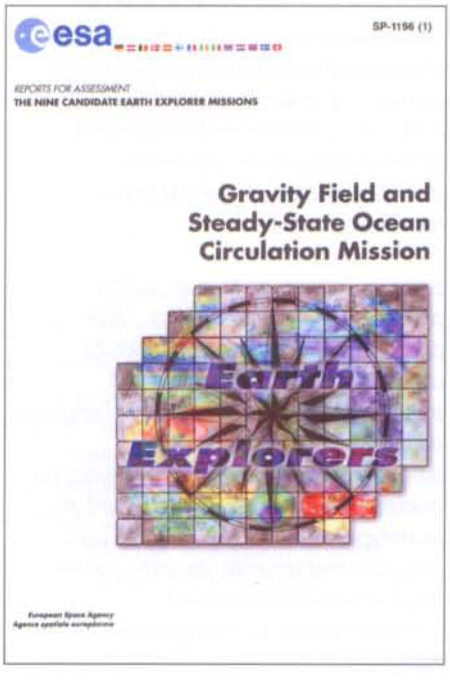
L'essai du modèle d'identification (EM) du terminal, mené conjointement avec celui conducted. The electrical models are in production, to be delivered at the end of the year, and manufacture of the structural models has commenced.

Integral

The prime contractor for the spacecraft, Alenia Spazio (I), has continued its definition work, with the boundary condition of commonality with the XMM service module. In parallel, it has evaluated, jointly with the Agency, the proposals received in response to competitive Invitations-to-Tender for Integral-specific items. The results of these actions will be reflected in the Preliminary Design Review data package and the Phase-C/D proposal to be submitted in early June.

The first review of the payload has been completed, resulting in agreed instrument-to-spacecraft technical interface definitions.

Turning to the ground segment, a similar review process was initiated for the Science Data Centre that will process Integral's instrument data. The remainder of the ground-segment effort has focussed on the definition of implementation plans in response to project requirements.



Artemis

Satellite

The primary structure of the structural model (SM) has been delivered to BPD in Colleferro (I), for integration of the SM propulsion subsystem and instrumenting of those elements that will be inaccessible later. This activity, which also involves CASA (E) and Alenia (I), is planned to be completed by the beginning of July this year. The SM primary structure will then be returned to CASA in Madrid for final assembly and preparation for shipment to ESTEC, where it will start its environmental test campaign at the end of August.

The engineering-model (EM) assembly, integration and test campaign has started in the ALS facilities. To avoid duplication of the integration and dismounting of panels from the payload dummy support structure to the EM, the S-band/Ka-band Data Relay (SKDR) payload has been integrated directly on the spacecraft. The Test Readiness Review (TTR) of this activity was successfully completed at the end of May.

By using this approach, the SKDR payload test campaign is being performed in parallel with the integration and testing of the platform subsystems. Integration and testing of the Power Control and Distribution Subsystem (PCD), elements of the ion-propulsion subsystem, and interface verification with the onboard data-handling bus are currently in progress.

Ground segment

A proposal to merge the Artemis ground segment with the satellite's main development phase (C/D) contract was approved by the Agency's Industrial Policy Committee (IPC) on 8/9 May.

The scope of this contract, which is the responsibility of ALTEL as a subcontractor to Alenia, is:

- The procurement of the Artemis routine-phase facilities, consisting of the Primary TTC Station and Operations Control Centre, to be located at Fucino (I) and in Rome, respectively, and the associated communications network.
- The provision of the S-band backup TTC station at Fucino.
- The provision of the launch and early-orbit phase (LEOP) ground-segment facilities, consisting of a LEOP operations control centre located in Rome, and an S-band LEOP network.
- System facilities and pre-launch operations preparation.
- Control of the satellite from injection into transfer orbit, LEOP, commissioning, and three years of on-station operations.

Indra Espacio (E) is the main contractor for the Primary TTC Station's design, development and system assembly, integration and testing, with Rymsa (E) as subcontractor for the antenna subsystem and Laben (I) for the baseband subsystem. Equipment suppliers include ERA (UK) and MAC (I).

Nuova Telespazio is responsible for the design and development of the operations control centres, operations preparation and execution. The subcontractors include Dataspazio (I), GMV (E) and ELCA (CH) for the OCC software.

Telespazio will also receive direct technical support and consultancy services from ESOC.

Silex LEO terminal

Integration of the Silex LEO flight terminal is proceeding well. Environmental testing will start in mid-July and will be completed before the end of the year.

The testing of the engineering-model (EM) terminal together with the Spot-4 EM spacecraft has produced excellent results. In particular, the EMC tests have shown that no corrective actions need to be implemented.

Tests to demonstrate correct operation of the Silex EM terminal on Spot-4 together with the Spot-4 ground segment and the Silex ground segment in Redu (B) are currently underway.

EOPP

Future programmes

Nine 'Reports for Assessment' (ESA Special Publication SP-1196, Vols. 1 – 9) on the agreed candidate Earth Explorer missions were issued in April. These documents, established with the support of Mission Working Groups and industrial studies, formed the basis for a wide consultation with the European Earth Science Community, which culminated in the Earth Explorer Mission Users Consultation Meeting in Granada (E) on 29 – 31 May.

du modèle d'identification du satellite Spot-4, a donné d'excellents résultats. En particulier, les essais EMC ont montré qu'il n'était pas nécessaire d'avoir recours à des mesures correctives.

Des essais sont en cours pour vérifier le bon fonctionnement du modèle d'identification du terminal Silex sur Spot-4 avec le secteur sol Spot-4 et le secteur sol Silex à Redu (B).

EOPP

Programmes futurs

Neuf 'Rapports d'évaluation' (Publications spéciales de l'ESA SP-1196, vol. 1-9) ont été publiés en avril sur les missions candidates d'exploration de la Terre retenues. Ces documents, établis avec le soutien de groupes de travail 'mission' et d'études industrielles, ont servi de base à une large consultation des spécialistes européens des sciences de la Terre, dont le point culminant a été la réunion de consultation des utilisateurs des missions d'exploration de Terre, organisée à Grenade (E) du 29 au 31 mai.

La prolongation ultérieure de l'EOPP au-delà de la mi-1996 continue de faire l'objet de discussions avec les délégations.

Campagnes

Les préparatifs de la campagne INDREX-96, dont l'objet est de mettre au point un 'Système de télédétection et de surveillance pour la gestion des forêts et l'utilisation des sols en Indonésie', sont maintenant bien avancés.

Envisat/Plate-forme polaire

Plate-forme polaire (PPF)

Les activités relatives à la plate-forme polaire ont avancé dans trois grands domaines:

- *L'intégration finale du modèle structurel a eu lieu chez Matra Marconi Space à Bristol (GB). Le modèle a été ensuite expédié au centre d'essais de l'ESTEC où le programme d'essais mécaniques a commencé. L'essai de recherche de modes vibratoires est déjà terminé et les premiers résultats font apparaître une bonne corrélation avec les prévisions. Le programme d'essais se poursuit comme prévu.*
- *Les derniers essais de recette du modèle d'identification du compartiment des équipements de charge utile (PEB) sont en cours chez Dornier (D). Les difficultés rencontrées au cours des essais de logiciels et de compatibilité électromagnétique (EMC) pourraient entraîner un retard dans la livraison du PEB à Matra Marconi Space (B) pour les activités ayant trait à la plate-forme polaire.*
- *L'intégration du prototype de vol du module de servitude chez Matra Marconi Space à Toulouse (F) est quasiment terminée, à l'exception de deux ou trois unités qui connaissent des problèmes de fabrication et seront livrées avec un certain retard.*

En complément des activités ci-dessus axées sur les modèles, un travail important a été réalisé au niveau technique et gestionnel pour déterminer s'il était possible de réduire les coûts du programme par l'allègement de certaines activités ne présentant pas de caractère indispensable. Ces études ont permis de dégager des économies non négligeables, assorties toutefois d'une légère augmentation du risque technique. Les restrictions financières imposées par les délégations ont également obligé l'Agence à renégocier les conditions de paiement avec l'industrie.

Charge utile d'Envisat-1

Le programme relatif aux modèles structurels a bien avancé ces derniers mois avec un accroissement du nombre des essais réalisés au niveau des unités et de l'assemblage.

La structure principale de l'ASAR et du MERIS a été renforcée et les deux instruments ont passé avec succès l'épreuve des essais de qualification. Tous les modèles structurels des instruments sont désormais intégrés au modèle structurel de la plate-forme polaire, qui est prêt à subir les essais d'ambiance à l'ESTEC.

En ce qui concerne le programme relatif aux modèles d'identification, l'assemblage de la plupart des modèles des instruments a démarré. Un travail considérable a été accompli pour consolider les calendriers des modèles d'identification et des modèles de vol.

Les revues critiques de conception au niveau des unités et des instruments suivent leur cours.

De façon plus générale, des discussions se poursuivent au niveau du Conseil directeur du programme d'observation de la Terre et du Conseil de l'Agence en vue d'arrêter le profil de financement du programme pour les années à venir.

Secteur sol d'Envisat

Système

Au cours du premier semestre 1996, le Conseil directeur du programme d'observation de la Terre a insisté pour que l'équipe responsable du projet Envisat/plate-forme polaire réduise son coût-à-achèvement global tout en maintenant ses objectifs et en garantissant son plan de développement. Les objectifs de la mission n'ont pas été modifiés par ce plan de réduction des coûts: tous les instruments et toutes leurs caractéristiques de fonctionnement sont maintenus et le concept du secteur sol est confirmé.

Secteur sol

Les travaux portant sur la réalisation du secteur chargé des opérations en vol suivent leur cours. La revue critique de conception doit avoir lieu en octobre prochain.

En ce qui concerne la réalisation du système de gestion des données de charge utile (PDS), confiée à Thomson-CSF (F), l'étape de la revue critique de conception a été franchie en juin comme prévu. Toutes les activités ont été mises en route, à l'exception de l'approvisionnement du terminal terrien d'utilisateur qui recevra les données de charge utile relayées par le satellite Artemis (cet approvisionnement doit commencer en septembre) et des processeurs de données (seule l'unité ASAR est en cours de développement).

En ce qui concerne tous les autres processeurs des instruments, l'Agence procède à la définition des produits utilisateurs et des algorithmes de traitement correspondants avec l'appui de différents instituts, industriels et laboratoires spécialisés. Ces activités de documentation et de mise au point de prototypes ont déjà bien avancé pour plusieurs instruments, de sorte que les travaux de développement correspondants du PDS pourront bientôt commencer.

The future extension of EOPP beyond mid-1996 continues to be discussed with Delegations.

Campaigns

Preparations for the INDREX-96 campaign, which is aimed at development of a 'Remote Sensing and Monitoring System for Forestry Management and Land Cover in Indonesia', are now well advanced.

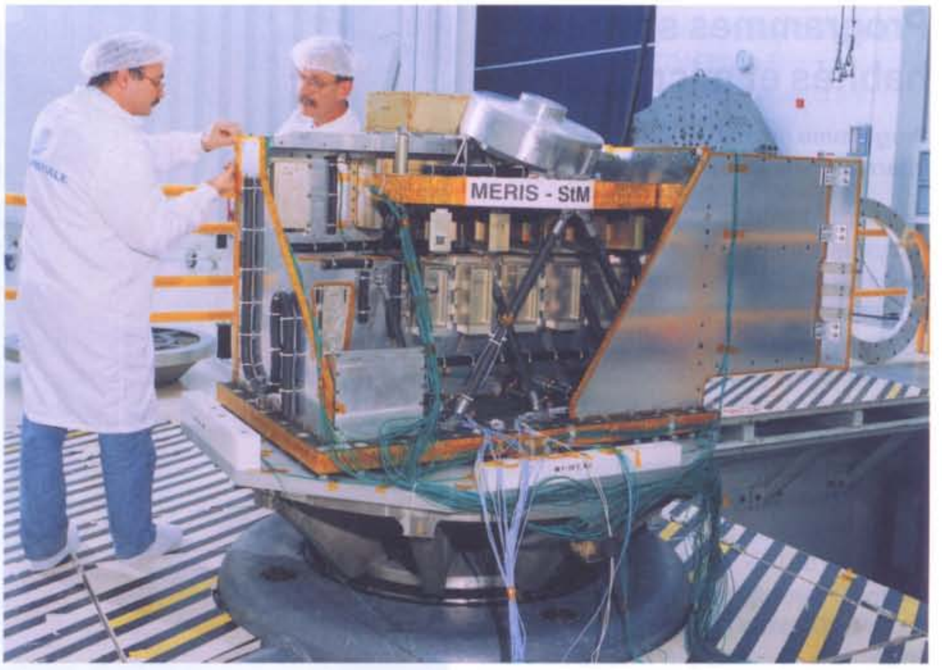
Envisat/Polar Platform

Polar Platform (PPF)

The Polar Platform activities have progressed in three basic areas:

- The structural model's final integration was completed at Matra Marconi Space in Bristol (UK), and it has since been transported to the ESTEC test facilities where the mechanical testing programme has begun. The modal-survey test has already been completed and the preliminary results indicate a good correlation with predictions. The test programme continues on schedule.
- The Payload Equipment Bay (PEB) engineering model is undergoing final acceptance testing at Dornier (D). Difficulties have been encountered in the software and EMC tests, which may delay the PEB's delivery to Matra Marconi Space (B) for Polar-Platform-level activities.
- The Proto-Flight Service Module integration is basically complete at Matra Marconi Space in Toulouse (F), except for two or three units which are experiencing manufacturing difficulties and will be delivered with some delay.

In addition to the above model-oriented activities, a significant managerial and engineering effort has been devoted to identify descoping opportunities in nonessential activities in order to reduce costs. These efforts have allowed appreciable cost savings to be achieved, albeit with a slightly increased development risk. In addition, funding limitations imposed by Delegations have resulted in a need to renegotiate payment conditions with industry.



Modèle structurel de l'instrument MERIS aux essais de vibration

Structural model of the MERIS instrument during vibration testing

Envisat-1 payload

The structural-model programme has seen significant progress in the last few months, with an increasing number of tests at unit and assembly level being successfully completed.

A reinforcement of the main structure for ASAR and MERIS has been implemented, and both instruments have successfully passed their qualification tests. All instrument structural models are now integrated on the Polar Platform structural-model spacecraft, ready for environmental testing in the ESTEC facilities.

As far as the engineering-model programme is concerned, assembly of most instrument models has started. A major effort has been made to consolidate the engineering-model and flight-model schedules.

Critical Design Reviews are now in progress at unit and instrument level.

On more general matters, discussions are still continuing at Earth Observation Programme Board and Council level in order to reach agreement on the Programme's funding profile for the coming years.

Envisat ground segment

System

During the first half of the year, the Earth Observation Programme Board put great pressure on the Envisat/Polar Platform Programme to reduce its overall cost-to-completion, whilst still maintaining the programme objectives and securing the development plan. The mission objectives have been preserved throughout this cost-reduction exercise, with all instruments and instrument performances being maintained and the ground-segment concept being reconfirmed.

Ground segment

The development effort for the Flight-Operation Segment is proceeding nominally, with the Critical Design Review planned for October.

The Payload Data Segment development, led by Thomson-CSF (F), has entered the Critical Design Review stage, as planned, in June. All activities have been kicked-off, except the User Earth Terminal procurement for reception of payload data via Artemis, which planned to start in September, and the data processors, where only the ASAR unit's development is in process.

For all the other instrument processors, definition of the user products and

Programmes spatiaux habités et microgravité

Programme de Station spatiale internationale (ISS)

Relations internationales

Une revue de conception par étapes de l'ISS s'est tenue à Houston en mars. Plusieurs problèmes en suspens ont été réglés, notamment en ce qui concerne les éléments à livrer à court terme par l'ESA à la Russie (système de gestion de données et bras télémanipulateur européen). La séquence d'assemblage de l'ISS a été mise à jour à l'occasion d'une autre revue, qui a eu lieu en mai, afin de prendre en compte le lancement du COF par la Navette spatiale au lieu d'Ariane-5, ainsi que le report de la date de lancement demandé par l'ESA.

Une série de réunions techniques a eu lieu avec la NASA. A cette occasion, des progrès appréciables ont été faits en ce qui concerne la résolution de problèmes potentiels liés à l'installation en orbite de bâtis de charge utile, aux analyses couplées dynamiques de la Navette et aux autres aspects techniques des interfaces.

Une importante réunion technique sur les interfaces entre l'ATV et la composante russe s'est tenue à Moscou. Un accord a été conclu sur le document des impératifs d'interface ATV/ISS, qui a été approuvé par l'ESA et RSC Energia, et la version initiale du document correspondant de contrôle des interfaces ATV/ISS a été établie par l'industrie.

Une directive de la Commission de contrôle de la Station spatiale établissant la base de référence de la fonction de rehaussement d'orbite de l'ATV dans le concept d'opérations et d'utilisation (COU), volume 1, a été publiée, marquant ainsi la première étape officielle de l'intégration de l'ATV dans la documentation de référence de l'ISS.

Une réunion a eu lieu avec la NASA/GSFC fin mai pour examiner le soutien que doit apporter au CTV le système américain de satellites de poursuite et de relais de données.

Secteur spatial de l'élément orbital Columbus (COF)

La définition et le transfert de certaines activités système de l'Allemagne à l'Italie ont été menés à bien et le prix définitif du contrat a été négocié afin de prendre en compte ce transfert ainsi que d'autres modifications mineures. Toutes les autres questions techniques, programmatiques et contractuelles en suspens relatives à la base de référence contractuelle du COF ont été résolues de manière satisfaisante au cours de la première quinzaine de mars et le contrat a été signé avec le maître d'oeuvre le 28 mars.

La qualification finale et la fourniture à la NASA du logiciel de la base de données mission mise au point pour le COF ont été menées à bonne fin. Ce logiciel est maintenant utilisé de manière opérationnelle dans les moyens de préparation de mission ISS à Houston.

L'adjonction éventuelle au COF de points d'ancrage (éléments permettant la fixation d'équipements complémentaires) est à l'étude. Des données devraient être communiquées par l'industrie en juin.

Polar Platform structural model in the ESTEC test facilities

Modèle structurel de la plate-forme polaire aux essais à l'ESTEC

Démonstrateur de rentrée atmosphérique (ARD)

L'assemblage et la qualification de l'ARD sont en voie d'achèvement. Certaines difficultés, dues à un retard de livraison de l'ensemble de propulsion de l'ARD, ont été résolues par un ajustement du calendrier d'intégration et de vérification.

Véhicule de transfert automatique (ATV)

La revue finale de phase B1 a eu lieu du 6 au 31 mai. Pratiquement toutes les actions engagées à l'issue de la première revue des impératifs système ont été achevées, à l'exception de quelques-unes, qui doivent encore être menées à terme et qui portent corresponding processing algorithms is being supported by expert laboratories, institutes and industry. These documentation and prototyping activities are already well-advanced for several instruments, allowing the corresponding PDS developments to be started in the near future.

Manned Spaceflight and Microgravity

International Space Station Programme (ISS)

International relations

An ISS Incremental Design Review was held in Houston in March. Several outstanding issues were settled, particularly with respect to the ESA-provided early-delivery items to Russia (Data Management System and the European Robotic Arm). The updating of the ISS Assembly Sequence to take into account the change of COF launch vehicle from Ariane-5 to Space Shuttle, together with the delayed launch date requested by ESA, was carried out at a subsequent review in May.

A series of Technical Interchange Meetings have been held with NASA, during which good progress was made with respect to the resolution of potential problems related to in-orbit installation of payload racks, Shuttle coupled loads analyses, and other technical interfaces.

An extensive Technical Interchange Meeting on the ATV/Russian Segment interfaces took place in Moscow. Agreement was reached on the ATV/ISS Interface Requirements Document, which was approved by ESA and RSC Energia, and the first draft of the corresponding ATV/ISS Interface Control Document was prepared by industry.

A Space Station Control Board Directive baselining the ATV re-boost role in the Concept of Operations and Utilisation (COU), Volume 1, has been issued, this being the first formal step in introducing the ATV into the ISS baseline documentation.

A meeting was held with NASA/GSFC at the end of May to discuss support to the CTV from the US Tracking and Data Relay Satellite System.

Columbus Orbital Facility (COF) Space Segment

The definition and transfer of system tasks from German industry to Italy has been successfully completed, and the final contract price has been negotiated to reflect this transfer, together with other minor changes. All remaining open technical, programmatic and contractual points with respect to the COF contract baseline were satisfactorily resolved during the first half of March, and the contract was signed with the prime contractor on 28 March.

Final qualification and delivery of the COF developed Mission Database software to NASA was successfully completed, and it has since been used operationally in the ISS Mission Build Facility in Houston.

The possible addition of 'hooks and scars' to the COF (fittings to allow attachment of additional features) is under consideration. Inputs from industry are expected in June.

Atmospheric Re-entry Demonstrator (ARD)

The ARD assembly and qualification neared completion. Some difficulties caused by the ARD propulsion equipment's late delivery were overcome by adapting the integration and verification planning accordingly.

Automated Transfer Vehicle (ATV)

The Phase-B1 final review took place over the period 6 – 31 May. Almost all actions stemming from the first System Requirements Review were closed out, with only few left to be completed, consisting mainly of complementary information to be provided by Russian industry and finalisation of cargo accommodation assessment.

ATV Rendezvous and Predevelopment (ARP)

Integration testing of the Global Positioning System and functional tests for the ATV Rendezvous and Prevelopment activities were successfully completed at ESTEC, with just one software problem still to be resolved. This problem was addressed with industry during the progress meeting held in May.

Crew Transport Vehicle (CTV)

The key results of the CTV Phase-A studies were presented to the Agency by the CTV prime contractor in May. The CTV Phase-B Procurement Proposal was approved by the Agency's Industrial Policy Committee in May, and the CTV Phase-B Invitation-to-Tender was prepared and mailed to industry accordingly.

X-CRV

There were discussions with NASA earlier in the year about the possibility of Europe and NASA cooperating in the development of a Crew Rescue Vehicle, based on a NASA-originated concept called X-CRV. A three-month study activity will be completed in July 1996 and the ongoing CRV/CTV study will take into account the conclusions of this exercise, if appropriate.

Ground segment

The procurement approach for the ground segment was presented to the ESA Manned Space Programme Board in April. A number of changes were proposed to the Executive's procurement approach, the most significant of which related to the inclusion of an option based upon a formal proposal submitted by some European National Centres just prior to the Programme Board's meeting. As a result, further technical clarifications were initiated to assess the technical and financial merits of the different options before submitting a final proposal for future procedure to the Participating States.

The procurement of a traffic-modelling tool was initiated. This tool is expected to be operational by the end of 1996 to support ISS traffic-model negotiations with NASA and the Russian Space Agency, and to assist in CTV mission definition.

A small short-term study has been started to analyse the various approaches and supporting rationale followed by the ISS partners for implementing their respective ground segments and operations management functions.

Early deliveries

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

Full agreement was achieved with the prime contractor and Russian industry for the detailed implementation into the DMS-R baseline of technical changes initiated by Russian industry in November 1995, including some revision of deliverables and adaptation of some delivery dates. Nonetheless, the overall DMS-R development schedule remains very critical with respect to committed delivery dates.

principalement sur des informations complémentaires à fournir par l'industrie russe et sur l'achèvement de l'étude d'installation des cargaisons.

Prédéveloppement du système de rendez-vous de l'ATV (ARP)

Les essais dintégration du système mondial de localisation GPS et les essais fonctionnels pour les activités de prédéveloppement du système de rendez-vous de l'ATV se sont déroulés de manière satisfaisantes à l'ESTEC, à l'exception d'un problème de logiciel, qui doit encore être résolu. Ce dernier a été examiné avec l'industrie lors de la réunion d'avancement qui s'est tenue en mai.

Véhicule de transport d'équipages (CTV)

Les principaux résultats des études de phase A du CTV ont été présentés à l'Agence par le maître d'oeuvre du CTV en mai. La proposition d'approvisionnement de phase B a été approuvée par le Comité de la politique industrielle de l'Agence au cours du même mois et l'appel d'offres correspondant a été établi et envoyé à l'industrie.

CRV-X

Des discussions ont eu lieu avec la NASA en début d'année quant à la possibilité d'une coopération entre l'Europe et la NASA pour la réalisation d'un véhicule de sauvetage des équipages basé sur un concept NASA et dénommé CRV-X. Une étude de trois mois s'achèvera en juillet 1996 et ses conclusions seront, le cas échéant, intégrées dans l'étude CRV/CTV en cours.

Secteur sol

La méthode d'approvisionnement du secteur sol a été présentée au Conseil directeur des programmes spatiaux habités de l'ESA en avril. Il a été proposé d'apporter un certain nombre de modifications au projet présenté par l'Exécutif, dont la plus importante a trait à l'intégration d'une option basée sur une proposition officielle soumise par certains centres nationaux européens juste avant la réunion du Conseil directeur du programme. En conséquence, un complément d'analyse technique a été lancé afin d'évaluer les avantages techniques et financiers des différentes options avant de soumettre aux Etats participants une proposition finale relative à la procédure future.

L'approvisionnement d'un outil de modélisation du trafic a été lancé. Cet outil, qui devrait être opérationnel d'ici la fin de l'année, devrait apporter une aide dans les négociations avec la NASA et l'Agence spatiale russe sur le modèle de trafic de l'ISS et dans la définition de la mission du CTV.

Une petite étude à court terme a été lancée afin d'analyser comment se présentent et quel intérêt offrent les différentes méthodes appliquées par les partenaires de l'ISS pour mettre en oeuvre leurs secteurs sol respectifs et les fonctions de gestion des opérations qu'ils utilisent.

Livraisons à court terme

Système de gestion des données pour le module de service russe (DMS-R)

L'ESA est parvenue à un accord complet avec le maître d'oeuvre et l'industrie russe sur le détail de l'intégration dans la base de référence du DMS-R des modifications techniques apportées en novembre 1995 par l'industrie russe; quelques éléments à livrer ont été révisés et certaines dates de livraison modifiées. Le calendrier général de réalisation du DMS-R reste toutefois très critique eu égard aux dates de livraison fixées.

Le retard dans la mise au point du jeu de puces du SPARC destiné au DMS-R est une cause de préoccupation; des entretiens exploratoires ont eu lieu avec une entreprise américaine qui pourrait les fournir en cas de besoin.

L'arrangement ESA/RKA qui sert de cadre juridique aux travaux de mise en oeuvre du DMS-R entre les deux Agences a été signé en mars.

Bras télémanipulateur européen (ERA)

Le contrat de phase C/D relatif à l'ERA a été signé le 19 mars et la revue préliminaire de conception (PDR) a démarré une semaine après, l'industrie ayant remis le 1er avril les documents de base du dossier de données.

Les équipes chargées de la PDR de l'ERA ont terminé leurs travaux dans la première quinzaine de mai et la Commission de la PDR s'est réunie le 15 mai. Elle a conclu que les objectifs de la PDR n'étaient pas atteints et a confirmé qu'il faudrait mener un certain nombre d'actions critiques définies par les équipes chargées de la revue avant de pouvoir clore officiellement la PDR. Le problème principal porte sur la maturité de la conception de l'ERA, jugée insuffisante pour pouvoir donner le feu vert à la phase suivante de réalisation. Ce manque de maturité tient essentiellement au délai trop court qui s'est écoulé entre les PDR au niveau sous-systèmes et la PDR de l'ERA, qui n'a pas permis d'intégrer les résultats dans le concept au niveau système.

Système de régulation d'ambiance et de soutien-vie (ECLS) pour le mini-module logistique pressurisé (MPLM) de l'Italie

La proposition industrielle de phase C/D a été reçue au premier trimestre 1996; après négociation, le contrat relatif à l'ensemble de la phase de réalisation a été signé en mai.

La revue des impératifs sous-systèmes a été menée à bien et l'Agence a approuvé toutes les spécifications et les plans de la base de référence, à l'exception du plan de gestion. Plusieurs revues préliminaires des équipements ont démarré, ces activités devant s'achever en juin.

Les négociations sur le document de contrôle des interfaces entre le MPLM et l'ECLS/MPLM ont révélé un problème technique risquant d'affecter la détection et l'extinction des incendies (fuite d'air). Ce problème a été résolu lorsque le Groupe 'Sécurité' de l'ISS a entériné la mise en oeuvre du concept proposé pour le MPLM.

Equipements de soutien de laboratoire

MELFI (Congélateur −80°C pour l'ISS): A la fin mars, les principaux composants du sous-système Brayton, y compris la boîte froide et le turbocompresseur, étaient intégrés. Après les derniers préparatifs et vérifications du banc d'essai, l'essai de fonctionnement a démarré début mai. Les résultats ont confirmé pour le moment la validité de la technologie adoptée et le choix des paramètres thermo-dynamiques.

MSG (Boîte à gants pour la recherche en microgravité): La phase-B et les activités relatives au modèle de développement sont terminées. La revue d'étude finale de la phase-B s'est tenue fin avril; le concept complet et l'évaluation analytique qui en a été faite ont été présentés, de même que les résultats des essais du modèle de développement. La proposition de phase C/D a été reçue fin mai et les préparatifs de cette phase sont en cours.

Hexapod: La revue de définition de la conception (DDR) de phase-B a eu lieu les 8 et 9 mai. Les activités lui faisant suite

The delay in the development of the SPARC chipset which is used by the DMS-R programme is giving cause for concern, and exploratory contacts with a US company as a possible backup supplier have been initiated.

The signature of the ESA/RKA Arrangement as the legal framework between the two agencies for the DMS-R implementation was achieved in March.

European Robotic Arm (ERA)
The ERA Phase-C/D contract was signed on 19 March, and the Preliminary Design Review (PDR) was initiated one week later with the release of the documents that formed the basis for the review of the industrial data package, delivered on 1 April.

The ERA Preliminary Design Review (PDR) team reviews were completed in the first half of May and the PDR Board met on 15 May. The Board concluded that the PDR objectives had not been met, and confirmed that a number of critical actions defined by the review teams had to be successfully completed before the PDR could be formally closed. The main problem related to the maturity of the ERA design, which was judged insufficient to release the next phase of development. This appeared to be caused primarily by the interval between the subsystem PDRs and the ERA PDR, which had been too short to incorporate the results into the system-level design.

Environmental Control and Life-Support System (ECLS) for the Italian Mini-Pressurised Logistics Module (MPLM)
The Phase-C/D industrial proposal was received in the first quarter of 1996 and, following negotiation, the contract for the full development phase was signed in May.

The Subsystems Requirements Review was completed and all baseline specifications and plans were approved by the Agency, with the exception of the management plan. Several equipment Preliminary Design Reviews were initiated; completion is planned in June.

During negotiation of the MPLM-ECLS/MPLM Interface Control Document, a potential technical problem emerged relating to fire detection and suppression (air leakage). This was subsequently resolved through the ISS Safety Panel endorsement of MPLM proposed design implementation.

Laboratory Support Equipment
MELFI (Minus Eighty Degree Centigrade Laboratory Freezer of the ISS): Major components of the Brayton subsystem including the cold box and the turbomachine were integrated at the end of March. Following the test-bench final preparation and checkout, the performance test was started in early May. The test results so far have confirmed the validity of the technology selected and the choice of thermodynamic parameters.

MSG: The Microgravity Science Glovebox (MSG) project has completed its Phase-B and development-model activities. The Phase-B Final Study Review took place at the end of April; the full design and its analytical assessment was presented together with the results of the development-model testing. The Phase-C/D proposal was received at the end of May and preparations are underway for this phase's initiation.

Hexapod: The Phase-B Design Definition Review (DDR) presentation took place on 8/9 May. The follow-on activities will be completed by June 1996. The Phase-B Final Review is scheduled for December.

Utilisation

At the level of coordination of payloads to be provided by ESA user programmes and by agencies funded through national programmes, the terms of reference are being drafted for a European Utilisation Board (EUB) to be set up by the Manned Space Programme Board. The EUB's main tasks will be to recommend guidelines and priorities on the European use of the ISS and to provide the PB-MS with a five-year European Partner Utilisation Plan (PUP) for decision. The US has already agreed upon a first version of the US PUP. The various Partner Plans will be merged at multilateral level to form a final Consolidated Operations and Utilisation Plan (COUP).

Microgravity Programmes

European Microgravity Research (EMIR I and II)
The EMIR programme has been authorised in phases: the first phase (EMIR I) covers the period 1995 through 1997/98, and the second phase (EMIR II, still in the approval cycle) is planned to cover the period 1996 through 2001. The matter of subscription will be discussed at the 48th meeting of the Microgravity Programme Board in June 1996.

The Biorack has been flown for the fourth time, carrying 10 biological experiments. It was accommodated in Spacehab on the third Shuttle mission to MIR, from 22 to 31 March. The Diffusion Coefficient Measurement Facility (dedicated to measuring the diffusion coefficient of mercuric-iodide and accommodated in a 'get-away special' cannister) was flown on the STS-77 Shuttle mission.

Microgravity Facilities for Columbus (MFC)
The principal elements of the multi-user facility development programme covering the period 1997 through 2002 are a Materials Science Laboratory, a Biolab, and a Fluid Science Laboratory. The necessary funds will become available in 1997. The current Phase-B studies are financed from the EMIR I programme.

The Mir station

La station Mir

s'achèveront d'ici juin 1996. La revue finale de la phase B devrait avoir lieu en décembre.

Utilisation

Afin de coordonner l'approvisionnement des charges utiles par les programmes utilisateurs de l'ESA et par des programmes nationaux financés par les Agences, une Commission européenne de l'utilisation (EUB), dont le mandat est en cours de rédaction, doit être mise sur pied par le Conseil directeur des programmes spatiaux habités. Les tâches principales de l'EUB seront de donner des orientations et d'indiquer des priorités applicables à l'utilisation par l'Europe de l'ISS et de soumettre au PB-MS un plan d'utilisation (PUP) quinquennal du partenaire européen. Les Etats-Unis ont déjà adopté une première version du PUP américain. Les différents plans des partenaires seront fusionnés au niveau multilatéral dans un plan d'exploitation et d'utilisation unifié (COUP).

Programmes de recherche en microgravité

Programme européen de recherche en microgravité (EMIR-I et II)

Le programme EMIR a reçu l'autorisation d'être engagé par phases: la première (EMIR-I) s'étend de 1995 à 1997/98, tandis que la deuxième (EMIR-II, dont l'approbation est encore en cours) devrait s'étendre de 1996 à 2001. La question des souscriptions sera abordée à la 48ème réunion du Conseil directeur du programme de recherche en microgravité, en juin 1996.

Le Biorack, équipé de 10 expériences biologiques, a été embarqué pour la quatrième fois; il était installé dans le Spacehab, à bord de la troisième mission de la Navette vers MIR qui s'est déroulée du 22 au 31 mars. L'installation de mesure des coefficients de diffusion (spécialisée dans la mesure des coefficients de diffusion de l'iodure de mercure et logée dans un compartiment GAS) a pour sa part été embarquée à bord du vol STS-77 de la Navette.

Installations de recherche en microgravité pour Columbus (MFC)

Le programme de mise au point d'une installation multi-utilisateur, qui s'étend de 1997 à 2002, prévoit les principaux éléments suivants: un laboratoire de science des matériaux, un Biolab, un laboratoire de science des fluides. Les crédits nécessaires deviendront disponibles en 1997. Les études de phase-B actuelles sont financées sur le programme EMIR-I.

In Brief

Ariane-501: The Inquiry Board's Report

On 4 June 1996, Ariane-5's maiden flight ended in failure, some 40 seconds into the main flight sequence. At an altitude of about 3700 metres, the launcher veered from its correct flight path, broke up and exploded.

Mr Jean-Marie Luton, ESA's Director General, and Mr Alain Bensoussan, CNES's Chairman, immediately set up an independent Inquiry Board, which has now submitted its report.

The report begins by presenting the causes of the failure, analysis of the flight data having indicated:
- nominal behaviour of the launcher for the first 36 seconds
- simultaneous failure of the two inertial reference systems
- swivelling into the extreme position of the nozzles of the two solid boosters and, slightly later, of the Vulcain engine, causing the launcher to veer abruptly
- self-destruction of the launcher correctly triggered by rupture of the electrical links between the solid boosters and the core stage.

The chain of events, their inter-relations and causes have been established, starting with the destruction of the launcher and tracing events back in time towards the primary cause. These provide the technical explanations for the failure of flight 501, which lay in the flight control and guidance system. A detailed account is given in the report, which concludes that:

'The failure of Ariane-501 was caused by the complete loss of guidance and attitude information 37 seconds after start of the main engine ignition sequence (30 seconds after lift-off). This loss of information was due to specification and design errors in the software of the inertial reference system.

The extensive reviews and tests carried out during the Ariane-5 development programme did not include adequate analysis and testing of the inertial reference system, or of the complete flight control system, which could have detected the potential failure.'

Despite the series of tests and reviews carried out under the programme, in the course of which thousands of corrections were made, shortcomings in the system approach concerning the software resulted in failure to detect the fault. It is stressed that the alignment function of the inertial reference system, which served a purpose only before lift-off (but remained operative afterwards), was not taken into account in the simulations, and that the

Successful lift-off of the ill-fated Ariane-5 first test flight equipment and system tests were not sufficiently representative.

Without implicating the system architecture, the report makes a series of recommendations for ensuring that the launcher's software operates correctly. The Ariane-5 Programme will be taking action in line with all of these recommendations, as follows:

- correction of the problem in the SRI (inertial reference system) that led to the accident
- re-examination of all software embedded in equipment
- improvement of the representativeness (vis-à-vis the launcher) of the qualification-testing environment
- introduction of overlaps and deliberate redundancy between successive tests:
  - at equipment level
  - at stage level
  - at system level
- improvement and systematisation of the two-way flow of information:
  - up from equipment to system: nominal and failure-mode behaviour
  - down from system to equipment: use of equipment items in flight.

More specifically, the following corrective measures will be applied:
- to the inertial reference system:
  - switch-off or inhibition of the alignment function after lift-off
  - analysis/modification of processing, particularly on the detection of a fault (no processor shutdown)
  - testing to check the coverage of the SRI flight domain
- to the system qualification environment:
  - general improvement of representativeness through systematic use of real equipment and components wherever possible
  - simulation of real trajectories on SRI electronics.

In addition, the following general measures will be taken:

- critical reappraisal of all software (flight program and embedded software)
- review of mechanisms for managing double failures
- improvement of facilities for acquisition and retrieval of telemetry data
- improvement of overall coordination relating to software.

The ESA Director General and CNES Chairman will be making a joint presentation of the plan of action put into effect and its programmatic consequences at a Press Conference in September.

Four More Successful Ariane Launches

The 86th Ariane launch (V86) took place successfully on Wednesday 15 May at 22:56 p.m. local time from the Kourou launch base in French Guiana. An Ariane-44L, equipped with four liquid strap-on boosters, placed the Indonesian telecommunications satellite Palapa-C2 and the Israeli telecommunications satellite AMOS into Geostationary Transfer Orbit (GTO).

The 87th Ariane launch took place just four weeks later, at 03:55 a.m. Kourou time on 15 June. This time, an Ariane-44P, equipped with four solid-propellant strap-on boosters, lifted the telecommunications satellite Intelsat-709 into GTO for the International Telecommunications Satellite Organisation (Intelsat).

Just over three weeks later, at 19:24 p.m. local time on 9 July, the next Ariane launch (V89) was underway. On this occasion, another Ariane-44L placed two telecommunications satellites, Turksat-1C and Arabsat-2A, into GTO.

The latest Ariane-4 launch (V90), carrying the telecommunications satellites Telecom-2D and Italsat-F2, took place on 8 August at 19:49 p.m. local time.

Europe to Provide Own Satellite Navigation Services

ESA, the European Commission and the European Organisation for the Safety of Air Navigation (EuroControl) are jointly developing EGNOS (European Geostationary Navigation Overlay Service). This European augmentation system for satellite navigation will provide civil GPS (Global Positioning System) and GLONASS (Russian satellite navigation system) users on land, at sea or in the air with improved accuracy, integrity and service availability.

Working together, the three entities are known as the European Tripartite Group (ETG). On 27 June, the ETG signed leases for the first two navigation transponders that will be used to broadcast EGNOS signals to users. These transponders are being flown by two Inmarsat-III satellites, located at longitudes of 64 deg East (Indian Ocean Region) and 15.5 deg West (Atlantic Ocean Region - East). Together they will cover not only the whole of Europe, but Africa, South America and most of Asia also. The Indian-Ocean satellite has been operational since 12 May 1996, and the Atlantic-Ocean satellite is scheduled for launch in August 1996.

The leases were signed, in the presence of the European Commission, EuroControl

Two Agreements Signed between ESA and Canada

Mr John Manley, Canadian Minister for Industry, and Mr Jean-Marie Luton, ESA's Director General, met in Ottawa on 10 July, in the presence of Mr W. Mac Evans, President of the Canadian Space Agency (CSA), to discuss current and future relations between Canada and ESA.

During the meeting, Mr Luton and Mr Mac Evans signed two Agreements on participation by Canada in two ESA programmes: the General Support Technology Programme (GSTP), and the Advanced Research in Telecommunications Systems Programme (ARTES). The Canadian contributions to these programmes will amount to some 8 million Accounting Units (15 million Canadian dollars) and will enable European and Canadian industry to cooperate in future in critical high-technology areas such as remote-sensing and satellite communications.

From right to left seated: Mr W Mac Evans and Mr Jean-Marie Luton; standing: Ms Diana Durnford (Special Assistant to the Minister), Mr John Manley and Mr Karl-Egon Reuter (Head of the ESA Cabinet).

'Today, we are making an investment in Canada's scientific, technical and industrial future which will have far-reaching benefits', said Mr Mac Evans. *'Industrial contracts and strategic alliances with key European space companies are some of the principal economic benefits this strategic investment provides'.* Mr Manley also stressed *'...the value of Canada's partnership with ESA, our second largest space partner. These agreements further cement a long-standing relationship that has resulted in economic benefits for Canadian industry'.*

Canada has been an ESA Cooperating State since 1979, and is currently the only non-European country participating directly in ESA programmes.

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and Inmarsat, by ESA, France Telecom and Deutsche Telekom, the two European signatories of the Inmarsat operating agreement which had submitted the EGNOS proposal to the Inmarsat Council. These leases run for five years, with the possibility of an extension for a further five years.

In its final set-up, EGNOS will provide Ranging, Integrity and Wide Area Differential Services:

- The Ranging Service will broadcast GPS-like navigation signals to improve overall satellite-navigation-service availability. For instantaneous position determination, a user has to receive signals from four satellites. Neither GPS nor GLONASS can provide this at all times and for all locations worldwide. EGNOS will help to fill this shortfall.
- The Integrity Service will broadcast range-error estimates for each GPS, GLONASS or EGNOS navigation signal. Without this EGNOS capability, information regarding the abnormal performance or failure of GPS or GLONASS would take 15 minutes or more to reach the user. The Integrity Service will enable users to decide much sooner whether a navigation satellite signal is out of tolerance, before potentially critical situations can arise.
- The Wide Area Differential Service will broadcast correction signals to improve the precision of satellite navigation. For civil users, the GPS signals are intentionally corrupted to lower the real-time precision from approx. 16 m to 100 m. The Wide Area Differential Service will establish a precision of 5 – 10 m.

The Ranging Service is planned to start in 1997. The other services will be phased in gradually between 1998 and 2000.

EGNOS itself will be composed of:

- The space segment: the two Inmarsat-III transponders, to be supplemented later to meet the extreme safety requirements for certain aircraft precision approaches to airports.
- The earth segment: Ranging and Integrity Monitors distributed over the service area will be connected to Master Control Centres, where the EGNOS signals will be generated. At least three such centres are needed to meet civil-aviation safety requirements. France Telecom's earth station at Aussaguel and that of Deutsche Telekom at Raisting will be used as primary access stations.
- The user segment: EGNOS standard receivers.

The contract for the development of the ranging function was awarded to the French company Thomson-CSF in July 1995. In December 1995, the same company was awarded another contract for the detailed design of the entire EGNOS infrastructure. A proposal for subsequent EGNOS development, system verification and testing will be submitted in the second half of 1996.

Within the ETG, ESA is responsible for the management of all development, deployment and technical-validation activities; EuroControl provides the civil-aviation user requirements and supports the certification process, while the European Commission consolidates all user requirements and oversees development of the EGNOS receivers and associated standardisation activities and trials, and supports access to the Inmarsat-III navigation transponders.

ESA and DARA Agree on Tenerife Optical Ground Station

An Agreement between ESA the German Space Agency (DARA) was signed on 30 June by Mr René Collette, Director of ESA's Telecommunications Programme, and Mr Jan-Baldem Mennicken, Director General of DARA. It concerns the provision of observation instruments for the new ground station at Izana (Tenerife, Spain), which was inaugurated the same day in the presence of the King and Queen of Spain.

Germany has supplied a 1-m Zeiss-Jena telescope, the dome for the building, and associated equipment to be used for the testing, calibration and operation of optical communications payloads flown on ESA's Artemis satellite, and for the observation of space debris.

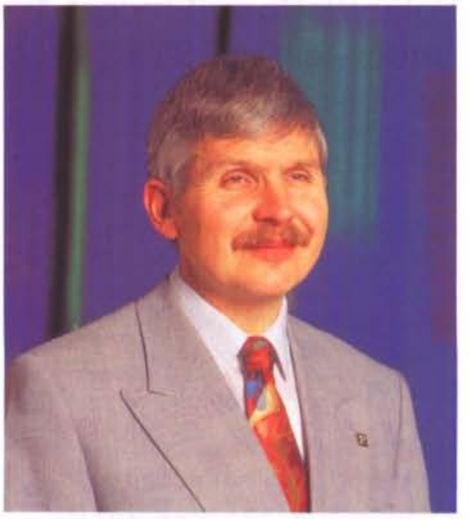
The essential roles of the Izana station, operated under an Agreement between ESA and the Instituto de Astrofisica de Canarias (IAC), apart from astronomical observations, include the receipt of laser signals from data-relay satellites and the observation/tracking of space debris. The space-debris work will be conducted by the IAC, DARA and ESA's European Space Operations Centre in Darmstadt (Germany).

Mr René Collette (seated, left) and Mr Jan-Baldem Mennicken (seated, right) at the Tenerife signing

Mr René Collette (left) greets Queen Sophia and King Juan Carlos

In the foreground, the observatory building (carrying the German dome) that will house the new instrumentation

ESA Council Elects New Chairman



Mr H.R. Parr

Hugo Ragnar Parr, currently Director General of the Research Department at the Norwegian Ministry of Industry and Energy, will be Chairman of the ESA Council for the next two years. Mr Parr was unanimously elected at the Council's 125th Meeting in Paris on 25/26 June 1996. He takes over from Mr Pieter-Gaele Winters of The Netherlands, whose term of office ended on 30 June 1996.

Hugo Parr, born on 23 April 1947, holds a Degree in Physics from the University of Washington (1969) and a Doctorate in Solid-State Physics from the University of Oslo (1976). He has been a member of the ESA Council since 1995.

Major Milestone for Hipparcos

On 8 August, seven years to the day after the Hipparcos satellite's launch, and just three years after the end of satellite operations, ESA and the Hipparcos Science Team have announced the completion of the Hipparcos and Tycho Stellar Catalogues. The difficult but astrophysically extremely important task of measuring stellar distances and motions has been completely revolutionised by this highly successful ESA science mission, which has totally surpassed all of the scientific goals motivating its acceptance as an ESA project in 1980.

The finalisation of these unique and highly complex stellar Catalogues has been completed almost exactly according the schedule predicted before launch for the Hipparcos Catalogue, and about a year in advance of the pre-launch prediction for the Tycho Catalogue. ESA acknowledges the intensive and sustained effort by the many Hipparcos consortia scientists involved in the Catalogue preparation and finalisation tasks under the scientific consortia leaders Prof. Erik Hoeg (Copenhagen), Prof. Jean Kovalevsky (OCA, CERGA), Dr Lennart Lindegren (Lund), and Dr Catherine Turon (Meudon).

With the Hipparcos and Tycho Catalogues finalised, the first phase of the Hipparcos data release (concerning proposals made by members of the scientific consortia) was initiated in August. The release of data to 1982 proposers will take place later in the year or early in January 1997.

Summary of the Hipparcos and Tycho Stellar Catalogues

Measurement period	1989.85 – 1993.21
Catalogue epoch	J1991.25
Reference system	ICRS
Coincidence with respect to ICRS (all three axes)	±0.6 milliarcsec (mas)
Proper motion deviation from inertial (all three axes)	±0.25 mas/yr
Estimated systematic errors in astrometry	<0.1 mas
Hipparcos Catalogue	
Number of entries	118 218
Mean sky density	~3/deg^2
Limiting magnitude	V ~712.4 mag
Completeness	Up to V = 7.3 – 9.0 mag
Median precision of positions, J1991.25 (Hp<9 mag)	0.70 mas
Median precision of parallaxes (Hp<9 mag)	0.97 mas
Median precision of proper motions (Hp<9 mag)	0.80 mas/yr
10% (each of the five parameters) better than	0.47 – 0.66 mas
Smallest errors on the five astrometric parameters	0.27 – 0.38 mas
Distance determined to better than 10%	20 853 stars
Distance determined to better than 20%	49 399 stars
Median photometric precision (Hp, for Hp<9 mag)	0.0015 mag
Number of entries variable or possibly variable	11 597 (8237 new)
Number of solved or suspected double/multiple systems	23 882
Tycho Catalogue	
Number of entries	1 058 332
Mean sky density	~25/deg^2
Limiting magnitude	V_T ~11.5 mag
Completeness	V_T ~10.5 mag
Median astrometric precision (all stars), J1991.25	25 mas
Median astrometric precision (V_T < 9 mag), J1991.25	7 mas
Inferred ratio of external errors to standard errors	~1.0 – 1.2
Systematic errors in astrometry	<1 mas
Median photometric precision (V_T < 9 mag)	0.01 – 0.02 mag

Polar Platform/Envisat-1 Under Test at ESTEC

ESA's largest satellite is currently being tested at the European Space Research and Technology Centre (ESTEC) in Noordwijk (NL). The 10 m-high structural model of the Polar Platform has been undergoing tests in the Large European Acoustic Facility (LEAF), and modal survey testing (to identify the spacecraft's natural modes of vibration) is presently in progress.

The Polar Platform, which forms the basic carrier structure for the Envisat-1 payload complement, weighs 8 tons and will be launched by an Ariane-5 vehicle in 1999. Prior to launch, the flight unit of this very large Earth-observation spacecraft will also be at ESTEC for a seven-month test campaign during 1998.

The structural model is scheduled to undergo an extensive sequence of tests in the various specialised facilities at ESTEC and will therefore remain in Noordwijk until almost the end of the year. In October/ November, it will be the first 'customer' to use ESTEC's new Hydraulic Vibration Test Facility (HYDRA), which is presently in its final phase of construction.

Obituary

The Agency has learned with regret of the death, on 7 August 1996 in Bonn – Bad Godesberg, of Dr Alexander Hocker, former Director General of ESRO. Born in Schweinsburg, Germany on 29 April 1913, Alexander Hocker read law, political science and economics at the Universities of Innsbruck, Hamburg and Leipzig, before gaining his Doctorate from the Faculty of Law at Leipzig.

He became involved with ESRO from its earliest days, through his work with the Legal, Administrative and Financial Working Group of COPERS, which he chaired from 1961 until 1964. In 1964, he was appointed Vice Chairman of the ESRO Council, taking over the Chairmanship for the years 1965 – 1967.

In February 1971, he was appointed Director General of ESRO for a three-year term, which was subsequently extended until 30 June 1974.

Dr. A. Hocker

During his mandate as Director General, Alexander Hocker guided ESRO through a succession of important events in its history, including:

- the adoption of the so-called 'First Package Deal' by the ESRO Council in December 1971, reorienting the ESRO activities by introducing Application Satellite Programmes (Aerosat, Meteosat and Telecommunications) for the first time, and initiating work on a revision of the ESRO Convention, which ultimately became the ESA Convention in 1975;
- the Ministerial Meetings in Brussels in December 1972 and July 1973 (European Space Conference), which resulted in the approval of three major new programmes, namely the Ariane, Spacelab and Marots development programmes, and the decision to merge ESRO and ELDO into a single European Space Agency.

He will be remembered for these and his many other endeavours which played a pivotal role in shaping the futures of both ESRO and ESA.

ESA Astronaut to Fly on the Sixth Shuttle – Mir Docking Mission

ESA astronaut Jean-François Clervoy has been named by NASA as one of the six crew who will conduct the sixth scheduled docking of the US Space Shuttle 'Atlantis' with the Russian space-station Mir. This mission (STS-84), scheduled for May 1997, is part of NASA's Phase-One Program for the International Space Station.

Jean-François Clervoy, of French nationality, will serve as a Mission Specialist on the trip. The other five crew members, all NASA astronauts, will be: Charles Precourt (Commander), Eileen Collins (Pilot), and Carlos Noriega, Edward Lu and Mike Foale (all Mission Specialists).

The Space Shuttle, carrying the Spacehab double module, will remain docked to Mir for five days. During that time, supplies will be transferred to the station and samples and data from completed experiments will be stowed on the Shuttle for return to Earth.

It will be the second flight for Jean-François, who flew previously on STS-66, the Third Atmospheric Laboratory for Applications and Science (ATLAS-3), in November 1994. He joined ESA's Astronaut Corps, based at the European Astronauts Centre (EAC) in Cologne, Germany, in May 1992. After completing his introductory astronaut training programme at EAC, he entered NASA's Mission Specialist training programme at Johnson Spaceflight Center (JSC) in Houston and was part of the first international astronaut class, which graduated in August 1993.

European Flavour to Latest Space Shuttle Flight

When Space Shuttle 'Columbia' (STS-78) lifted off from Kennedy Space Center on 20 June, ESA had five major facilities on board and responsibility for more than half of the experiments to be conducted on this multi-discipline Life and Microgravity Sciences Spacelab Mission (LMS).

Jean-François Clervoy

The key objectives of the 16-day LMS mission were to study the effects of microgravity on the physiology, development and behaviour of living systems, and to conduct experiments in fluid physics, materials processing and the growth of protein crystals. Spacelab, developed and funded by ESA as Europe's contribution to NASA's Space Transportation System, provides astronauts with an ideal laboratory-like environment in which to conduct such research.

ESA-developed experiment and research facilities for this mission included the Bubble, Drob and Particle Unit (BDPU), the Advanced Protein Crystallisation Facility (APCF), the Advanced Gradient Heating Facility (AGHF) and the Torque Velocity Dynamometer.

The ESA facilities and experiments involved scientists from 10 countries, with Principal Investigators from Belgium, Canada, France, Germany, Italy, Spain, Sweden, Switzerland, the United Kingdom and the United States. The international Shuttle crew included Canadian astronaut Robert Thirsk and the French astronaut Jean-Jacques Favier as payload specialists. ESA astronaut Pedro Duque from Spain served as a ground crew communicator during the mission.

The STS-78 crew members and their alternates, during pre-mission training

Focus Earth

Two Different Views of the Landscape around Izmir, Turkey

J. Lichtenegger, T. Özalp & G. Calabresi
Data Utilisation Section, Remote-Sensing Exploitation Department, ESRIN, Frascati, Italy

The routine exploitation of the wealth of data delivered by ESA's ERS-1 and ERS-2 satellites, launched in 1991 and 1995 respectively, continues to proceed in a highly satisfactory manner. The SAR imagery in particular has been the target of much attention from the professional remote-sensing community, as well as the general public.

The multi-temporal image-interpretation concept, based on the combined use of images taken on different dates during the year to highlight changes that have taken place by displaying them in different colour tones, is proving a highly successful application. These **multi-season** images allow, for example, the identification of specific crops, because the nature of the vegetational growth during a particular season is very crop-specific. Another technique relies on combining images taken during the same season, but in different years. In this **multi-year** imagery, the landscape changes not only due to crop rotation, but also due to new construction, etc., which is easily detectable.

Izmir as seen in an ERS-1 SAR multi-season image

The image in Figure 1 is composed of three ERS SAR data sets acquired during the same year, but in different seasons. By assigning each data set an individual colour (red to data from 6 May 1995; green to data from 19 August 1995; blue to data from 6 January 1996), seasonal variations (e.g. in the vegetation) appear in various colour tones, whilst black and white represent areas without change.

The area imaged here includes the Gulf of Izmir to the top left. The white areas in the innermost part of the gulf delineate the city of Izmir itself.

The sea colours merely reflect wind conditions during the data acquisitions, with winds roughening the sea's surface causing increased radar backscatter. The prevalence of blue and magenta over the other colours is evidence that a strong wind was blowing from the north on 6 January, whereas the winds were rather weak on the other two acquisition days.

On the land, different kinds of vegetation cover and the presence of woods on hills and mountains are revealed by greenish/brownish tones (greenish for deciduous forest, brownish for pine or shrub). A limited ground survey is needed to interpret the colours appearing in the lowland areas: the red and yellow tones probably correspond, respectively, to cereal crops and to late crops like corn, sunflowers, tobacco, etc.

Looking at the image more closely, additional details that are useful for land-cover mapping can be detected: urban settlements appear in white, and railways and highways as dark lines. Particular features of Izmir, including its harbour, are clearly visible, such as the three water inlets to the sea, south of the town, and several ships at anchor or tied up along the dock (in colour). Red points indicate ships at these positions on 6 May 1995. Rectangular ponds, probably used for salt mining, are apparent along the northern shore of the gulf.

Geologically also, the image is very significant because of the various lithologies in the area. These are clearly evident thanks to both the hilly morphology and the colour enhancement. Lineaments are similarly detectable because of the presence of valleys and the discrimination provided by the colour changes.

Izmir as seen in an ERS-1 SAR multi-year image

The image in Figure 2 is composed of three ERS SAR data sets acquired during the same season, but in different years. By assigning each data set a particular colour (red to data from 23 April 1992; green to data from 8 April 1993; blue to data from 6 May 1995), variations are highlighted in colour tones, whilst black and white again identify areas where no changes have occurred.

The brownish tones of mountains and hilly terrain reveal that there have been no substantial changes during the three years. The greenish tones in the lowlands, however, indicate a high soil humidity at the time of the 8 April 1993 data acquisition.

Agricultural areas, with their clear field structure, can be recognised by their green, magenta, red, yellow and white colours. The green and white tones most likely correspond to unchanged crop types or land-use areas, whilst magenta, red and yellow tones reveal a change from early crops (cereals) to late crops (corn, tobacco, etc.). Greenish-blue hues represent the transition from late to early crops.

As far as changes in the urban areas are concerned, the green and blue dots probably indicate new settlements in the years between 1992 and 1995.

It is the Agency's hope that the uninterrupted availability of such unique data as these from the European Remote-Sensing Satellites ERS-1 and ERS-2, and their future successor Envisat, will serve as a constant source of encouragement for the remote-sensing user community's activities in the critical domain of environmental change detection.

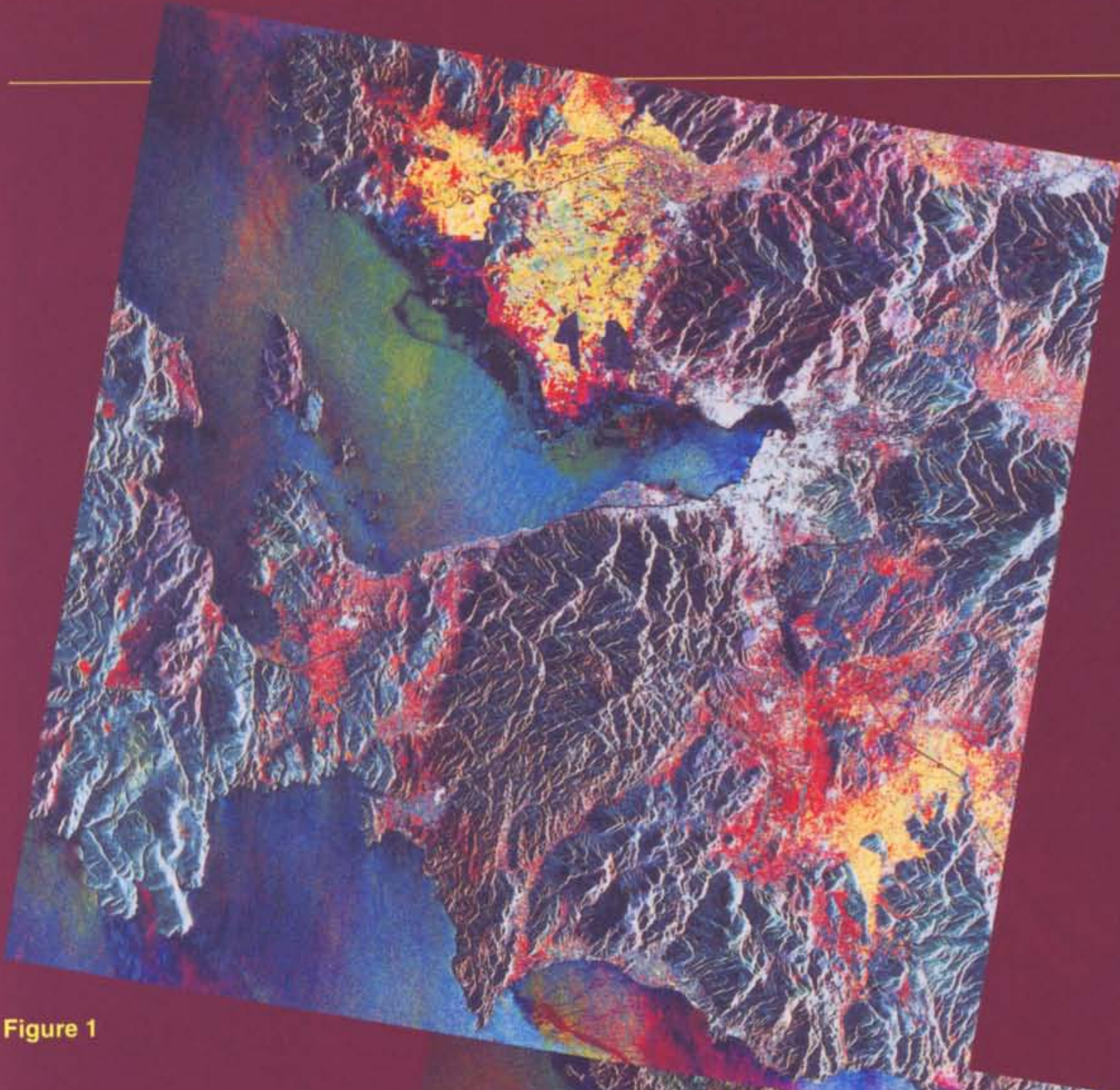


Figure 1

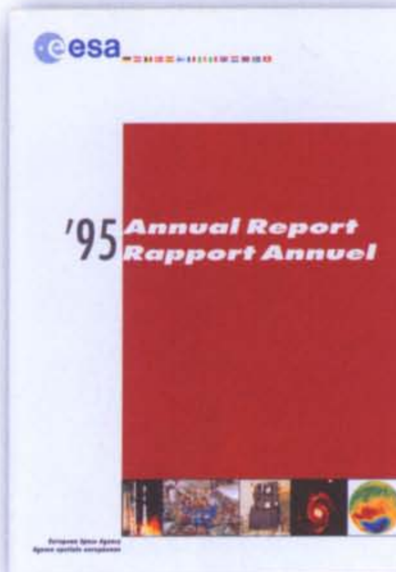
Figure 2

Publications

The documents listed here have been issued since the last publications announcement in the ESA Bulletin. Requests for copies should be made in accordance with the Table and Order Form inside the back cover.

Annual Report

ANNUAL REPORT/RAPPORT ANNUEL 1995 (MAY 1996)
BATTRICK B. & GUYENNE T.D. (EDS.)



Brochures

BENEFITS ON EARTH FROM SPACE AND SPACE TECHNOLOGIES (APRIL 1996)
WILLEKENS PH. (ED. B. BATTRICK)
ESA BR-117//13 PAGES
PRICE: 35 DFL

Newsletters

EARTH OBSERVATION QUARTERLY NO. 52, JUNE 1996
ED. T.D. GUYENNE
NO CHARGE

PREPARING FOR THE FUTURE VOLUME 6 NUMBER 2
ED. M. PERRY
NO CHARGE

MICROGRAVITY NEWS VOLUME 9 NUMBER 1
ED. B. KALDEICH
NO CHARGE

ECSL NEWS (EUROPEAN CENTRE FOR SPACE LAW) NO. 16, MAY 1996
ED. T.D. GUYENNE
NO CHARGE

Special Publications

PHYSICAL SCIENCE INSTRUMENTATION FOR MICROGRAVITY RESEARCH: AN OVERVIEW OF TECHNOLOGY DEVELOPMENT (MARCH 1996)
SAVAGE C.J. (ED. M. PERRY)
ESA SP-1188//45 PAGES
PRICE: 35 DFL

ESA Publications via Internet

Selected ESA publications are available via an ESA Publications Division 'home page' on a server run by the Agency's Information Retrieval Services Division-Exploitation Department at ESRIN in Frascati, Italy.

The address of the host is:

http://esapub.esrin.esa.it/esapub.html

Further information can be obtained from the IRS Help Desk at ESRIN:

Telephone: +39.6.94180300
E-mail: irshelp@mail.esrin.esa.it(Internet)
or: irshelp@esrin.bitnet

ESA'S REPORT TO THE 31ST COSPAR MEETING (JUNE 1996)
SANDERSON T. (ED. B. BURKE)
ESA SP-1194//245 PAGES
PRICE: 70 DFL

CATALOGUE OF ESA PUBLICATIONS IN 1995
ESA SP-1195//10 PAGES
PRICE: NO CHARGE

PROCEEDINGS OF THE ESA PRODUCT-ASSURANCE SYMPOSIUM AND SOFTWARE PRODUCT-ASSURANCE WORKSHOP, NOORDWIJK, THE NETHERLANDS, 19-21 MARCH 1996 (MAY 1996)
PERRY M. (ED.)
ESA SP-377//380 PAGES
PRICE: 80 DFL

PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON 'STEP' (TESTING THE EQUIVALENCE PRINCIPLE IN SPACE), PISA, ITALY, 6-8 APRIL 1993 (JULY 1996)
REINHARD R. (ED.)
ESA WPP-115//600 PAGES
PRICE: 100 DFL

PROCEEDINGS OF AN INTERNATIONAL CONFERENCE ON SPACECRAFT STRUCTURES, MATERIALS AND MECHANICAL TESTING, NOORDWIJK, THE NETHERLANDS, 27-29 MARCH 1996 (JUNE 1996)
BURKE B. (ED.)
ESA SP-386//1432 PAGES (3 VOLS.)
PRICE: 100 DFL

PROCEEDINGS OF THE FOURTH CIRCUMPOLAR SYMPOSIUM ON REMOTE SENSING OF THE POLAR ENVIRONMENT, LYNGBY, DENMARK, 29 APRIL - 1 MAY 1996 (JULY 1996)
GUYENNE T.D. (ED.)
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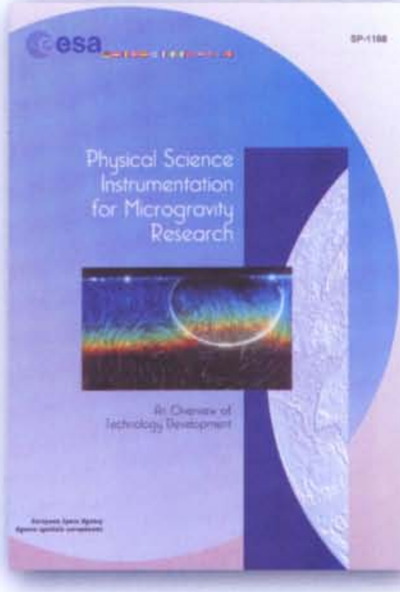

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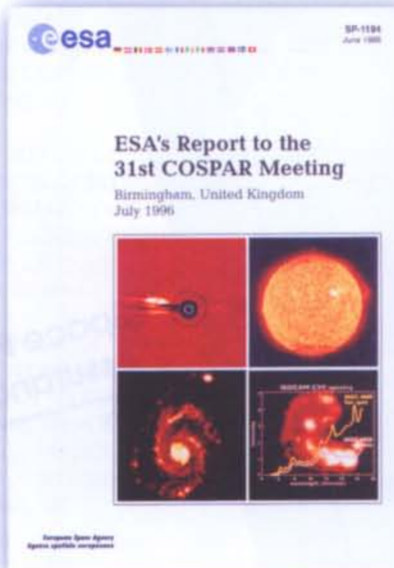

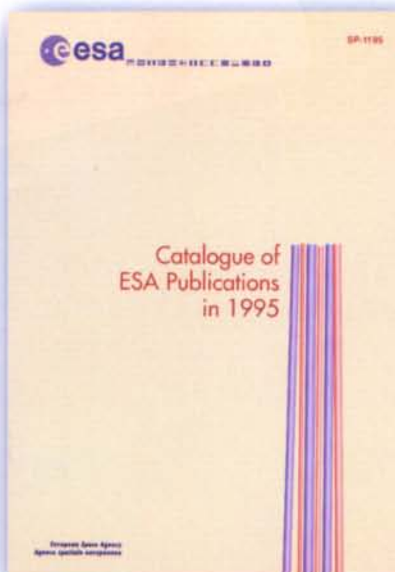

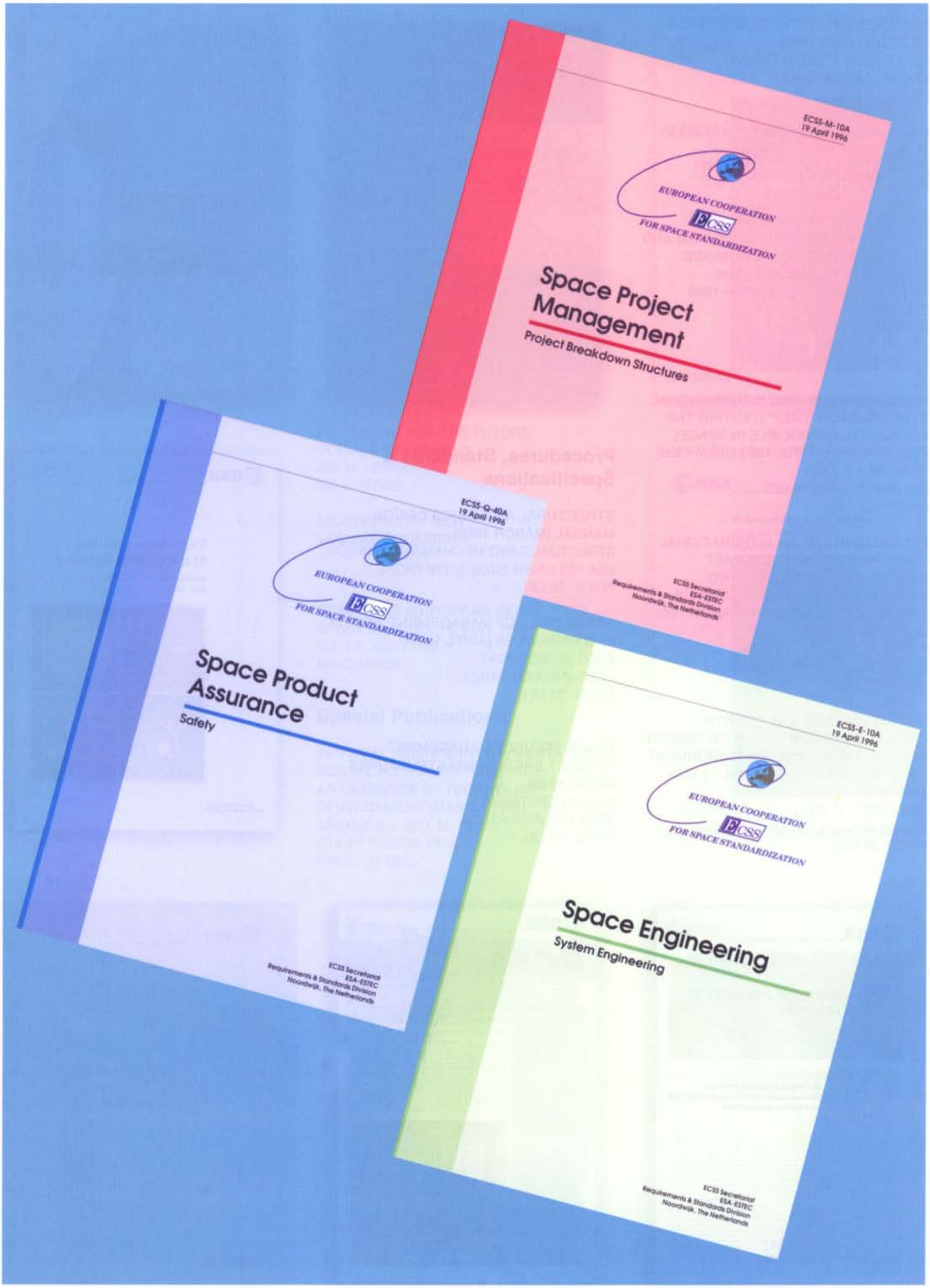
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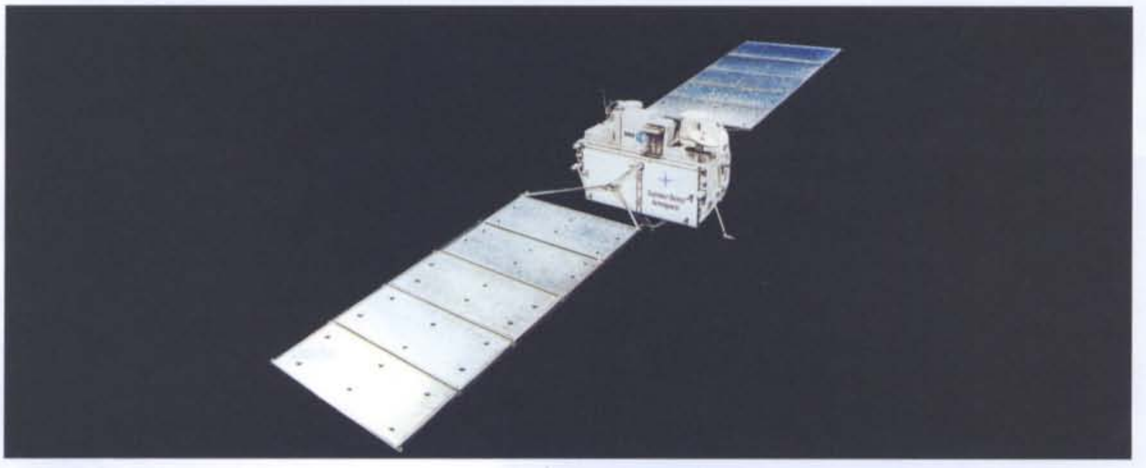

EURECA in-orbit operating configuration

Spacecraft Capabilities and Resources

Mass:	Total:	4500 kg
	Available to payload:	1000 kg
Orbit:	Shuttle-compatible	(typically 525 km, 28.5°)
Mounting surface:	Available to payload:	4.5 m^2 total
	Standard mounting panel:	0.7 m x 0.7 m
Volume:	Available to payload:	8.5 m^3
Power:	Solar array output:	5000 W
	Available to payload (EoL):	1000 W continuous/1500 W peak
Thermal Control:	Active/Passive:	liquid cooling loop/multi-layer insulation
Data Management:	Downlink to g round station:	256 kbps, S-band
	Uplink (commands):	2 kbps, S-band
Attitude control:	Sun pointing (z-axis); Pointing accuracy:	± 1° (3 sigma)
Microgravity environment:		10^{5} g < 1 Hz; 10^{3} g > 100 Hz
Nominal mission duration:		6 months operations; variable in-orbit stay time

We are actively soliciting the participation of potential users in a reflight mission which we could carry out by the end of this decade. It is assumed that major national and international space agencies will be involved. If you are a researcher in space science or technology and looking for a flight opportunity, EURECA is the solution. A detailed description of the spacecraft performance and resources is already available at Dasa, including a section for you to notify us of your interest. At Dasa we mean business in space.

(Photo: NASA/ESA)

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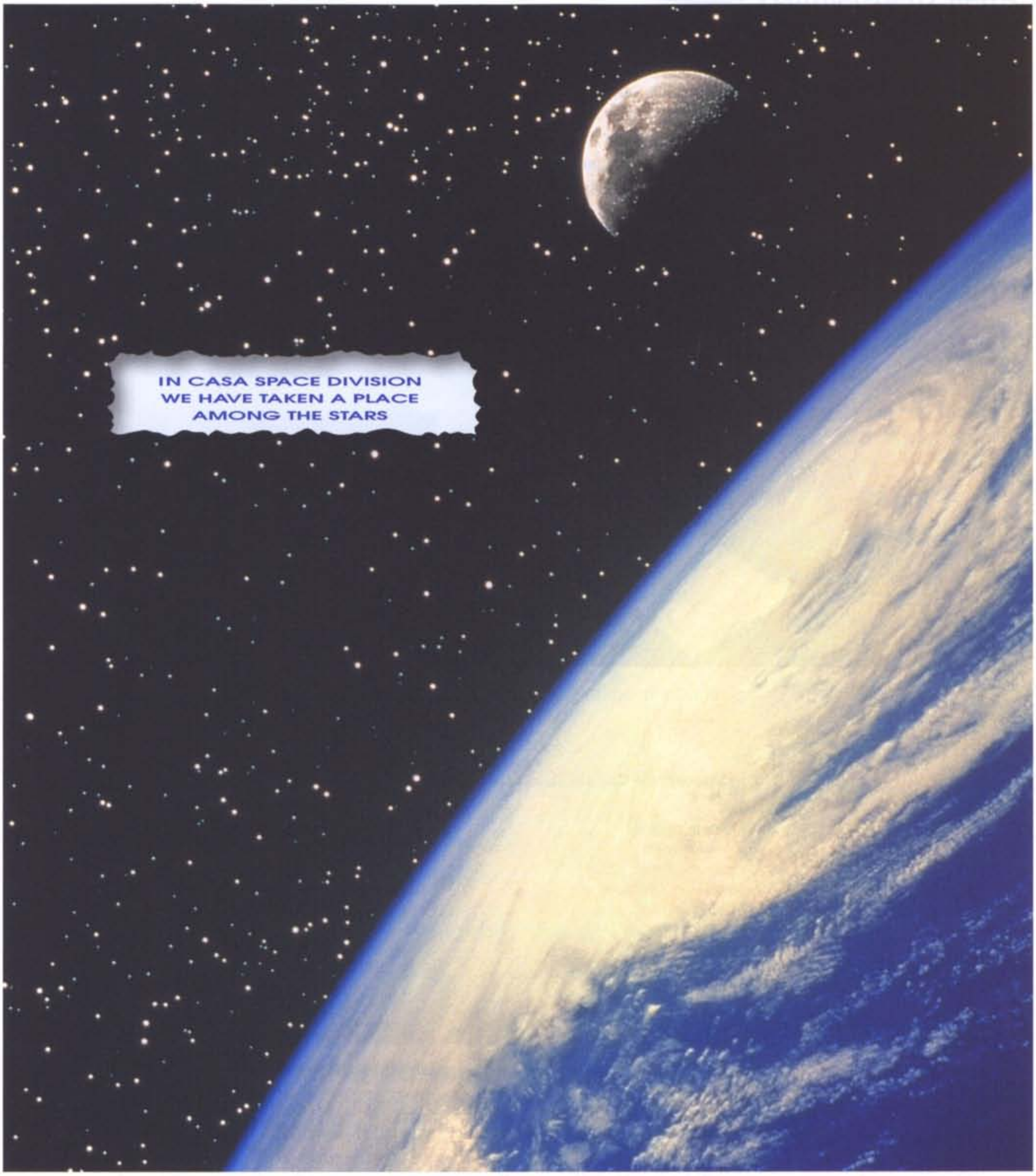
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